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THESIS

THE EFFECT OF CIRCUMFERENTIAL TUBE WALL HEAT CONDUCTION UPON LAMINAR FILMWISE CONDENSATION ON THE OUTSIDE OF CONDENSER TUBES

by

Howard Michael Holland

December 1980

Thesis Advisor: R. H. Nunn

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ABSTRACT

This thesis describes the results of a theoretical study to predict the thermal behavior of an internally-cooled tube in a condensing vapor.

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I. INTRODUCTION

A. BACKGROUND INFORMATION

As the size, complexity, and hence the cost of modern warships have grown in the last thirty years, advances in basic research have been made and the computer has become a useful tool to the researcher and designer. The application of up-to-date research and computer technology to the design of modern warships is common but there remain major, costly components relatively unchanged and unreviewed in decades. It is in the interest of the Navy to ferret out these components and re-examine them.

One such component is the naval condenser. The basic engineering developments currently used to design naval condensers are from the Heat Exchanger Institute (H.E.I.) Standards for Steam Surface Condensers [1] and the standards of the Tubular Exchanger Manufacturers Association (T.E.M.A.) [2]. The Navy has further utilized the H.E.I. information in the Design Data Sheet (D.D.S.) [3]. While these standards have proven reliable, their performance margins and extensive use of averaged values may result in a larger, costlier condenser at no increase in performance and with an unnecessary margin of reliability. These performance margins, once necessary to insure reliability, are now called into question as the mysteries of condensation are unravelled.

It is for the purpose of reducing the size of the condenser that many researchers are trying to increase the heat transfer rate per unit of condensing surface area.

B. CONDENSATION IN A NAVAL CONDENSER

A typical naval condenser uses the heat transfer mechanism of filmwise condensation to the outside of horizontal, cylindrical tubes. Dropwise condensation is therefore not considered in this thesis.

The inside of the tube has single-phase turbulent forced convection heat transfer. The correlations associated with this phenomenon are accurate enough to justify confidence in their use. The fouling of the inside of the tube is poorly understood, and varies greatly, so that a necessary design allowance is made and a performance margin created. The heat transfer through the tube wall itself is by conduction, a classical problem in cylindrical coordinates, and can be calculated as accurately as the properties of the tube material and the surrounding heat transfer coefficients are known.

Aside from a greater knowledge of coolant-side fouling and how to control it, it is largely on the steam side of the tube that advances of knowledge can be reasonably expected. Here there are three important phenomena. The first is the transfer of heat through a thin layer of condensate from a vapor, either quiescent or flowing, which causes that vapor to lose its latent heat of vaporization and join the film of

condensate on the tube. As condensing particles join this liquid layer they retain some, none, or all of the momentum they possessed as a vapor. The dynamic interaction of the vapor and the liquid under both forced flow and quiescent vapor conditions presents a formidable problem to the researcher. A second phenomenon on the steam side of the tube is the presence of noncondensible gases which complicates and usually degrades the performance of the condenser. The third phenomenon is the inundation of a condenser tube by "condensate rain," or condensate condensed elsewhere in the condenser which, as it makes its way to the hotwell, impinges upon the condenser tube.

C. IMPROVING THE HEAT TRANSFER

If the rate of heat transfer for a given area of condensing surface were to be increased, then the total size of a condenser could be reduced. The result would be savings in space, weight, and possibly cost. Various methods of increasing the heat transfer in a naval condenser have been proposed. Among these are:

1. Reducing the Internal Fouling

The reduction of internal fouling would certainly increase the rate of heat transfer. While various tube metals and chemical treatments to the coolant side of the condenser can reduce fouling, operational and other considerations have prevented their use in naval condensers. Aside from mechanical cleaning, no acceptable method of significantly

reducing marine fouling in a naval condenser has presented itself.

2. Eliminating Noncondensible Gases

The elimination or reduction of noncondensible gases in the condensing steam would be expected to increase the heat transfer rate. It is a fact of realistic operation in a marine environment that noncondensible gases cannot be eliminated. There is room for improvement in their continual removal from the condenser by air ejector devices. As long as complicated systems with mechanical seals are used in the shipboard environment, some amount of noncondensible gases will be in the condenser.

3. Enhancing Heat Transfer

a. Shaping of Tubes

Various ingenious shapes of tubes have been demonstrated to increase heat transfer rate for a given amount of tube surface area. Complications arise from these tubes, however, not the least being a sharp increase in the pumping power required to maintain an adequate coolant flow rate.

b. Promoting Dropwise Condensation

The use of various promoters upon the tube outer surface to prevent the forming of a liquid film, thus keeping the condensate in droplet form, has been proposed and demonstrated by many authors. Since it is not the intention of this thesis to examine the effect of this phenomenon, suffice it to say that until now there remains a question as to whether

any promoter has demonstrated the robustness to withstand continued, long-term use.

4. Eliminating or Reducing Inundation

Since condensers are formed with banks of tubes, it is inevitable that condensate draining from one tube should impinge upon some other lower tube. The effect of this in filmwise condensation is normally to thicken the condensate film and to reduce the rate of heat transfer. The proper placement of collection trays or baffles is of great importance in channelling falling condensate away from lower tubes. The number and placement of these collection trays is not examined in this thesis.

5. Utilizing High Vapor Velocities

In many regions of a naval condenser, vapor velocities of 300 ft/sec or more may occur. These high velocities create a forced flow situation on the steam side, thin the film of condensate, and generally increase the heat transfer coefficients on the steam side. The higher velocities also cause complications, one of which is the separation of the vapor boundary layer causing the condensate film to thicken suddenly. The heat transfer in the region of the tube which is after the vapor phase separation point is relatively unknown.

D. REVIEW OF GENERAL RESEARCH IN CONDENSATION

In analyzing the condensation of steam on tubes, the cornerstone of research was laid by Nusselt [4] who analyzed

a quiescent vapor condensing on a vertical flat plate and on a horizontal cylinder. Nusselt's analysis allowed for no interfacial shear stress between the flowing condensate and the condensing vapor. He also used a constant tube wall surface temperature.

Rohsenow, et al., [5] later expanded this work to include the effect of vapor shear at the vapor-liquid interface upon the condensation rates. This analysis was for a vertical flat plate of uniform temperature with either turbulent or laminar flow of condensate.

Sparrow and Gregg [6] conducted the first analysis of surface condensation using boundary layer theory. They included momentum terms in the condensate film analysis to account for acceleration of the flowing condensate. They showed that the momentum terms were insignificant under most conditions.

Koh, et al., [7] did further work allowing the falling condensate to drag the vapor along with it, while still using a constant wall surface temperature.

Shekriladze and Gomelauri [8] expanded upon the earlier work of Rohsenow, et al., [5], analyzing the effect of a flowing vapor upon laminar filmwise condensation in the absence of significant gravity effects. Their model used a constant wall surface temperature.

Denney and Mills [9] expanded this area of analysis to include the influence of gravity upon the condensate film, holding to a constant wall surface temperature.

E. RECENT WORK CONCERNING CONDENSATION ON TUBES

1. Vapor-Condensate Interfacial Shear Models

One of the areas of continual interest in condensation of steam on a tube is the question of the effect of the shear or drag of the condensing vapor upon the flowing condensate. Theories which attempt to quantify the interaction abound, but recent ones take one of two general forms.

The first type of model says that total shear is the result of the summation of dry friction shear of the vapor upon a bare tube and a shear caused by the condensing vapor retaining some, none, or all of its vapor phase momentum. The deceleration of this vapor as it joins the liquid layer causes this shear. Various authors [8, 10, 11, 12, 13,] subscribe to some combination of these two shears.

Other researchers [14, 15] subscribe to a theory which reaches more deeply into the molecular level interactions and in reality appears to be a more minute examination of the same idea. Using a Reynolds Flux concept, these authors state that for a flowing fluid there is a transport of momentum in a direction normal to the mass flow which is on the molecular level in laminar flow but involves larger amounts of fluid in turbulent flow. This transport is a function of temperature in laminar flow and of temperature and free stream turbulence in turbulent flow. As one of these cross-flowing particles approaches a solid wall, it is decelerated to a standstill. As it rebounds from the wall, it is reaccelerated. Thus,

an overall rate of condensation can be represented by superinposing a velocity perpendicular to the wall, similar to suction through a dry wall.

The latter theory includes within it a relationship between the rate of condensation and temperature drop that must necessarily occur in the process [14]. The former frictional shear force theories commonly assume that the outer surface of the condensate film is at the steam saturation temperature.

2. Wall Temperature Models

Fujii, et al., [16] display from their experimental data that tube temperature varies around the outside surface of the tube. In their calculations, however, they use averaged values for tube wall temperature and for the temperature-dependent heat transfer coefficients to calculate heat transfer.[1]

Nobbs and Mayhew [17] show that for steam flowing vertically downward, a variable temperature analysis results in a marked overall change in heat transfer. The state that earlier isothermal tube wall surface models were optimistic in their predicted heat transfer.

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[1] Since the writing of this theis, new results have been obtained by Fujii and his coworkers. The reader is referred to the Proceedings of the Workshop on Modern Developments in Marine Condensers, Naval Postgraduate School, 26-28 March, 1980.

Nicol and Wallace [13] show that local heat transfer coefficients are indeed a function of local tube surface temperature and recognize the importance of the circumferential path in heat conduction. In one of the first analyses to include this path of heat transfer, these authors apply a relaxation technique and iterative scheme, changing the temperature distribution and then the local heat transfer coefficients. It is interesting to note that their results show that when the circumferential heat conduction path is included, the average heat transfer coefficient rises about twenty-five percent.

Nicol, et al., [18] analyze steam crossflow upon condenser tube (Fig. 1) using a formulation wherein local tube surface temperatures are used to calculate local heat transfer coefficients. Thier results show that the variable wall temperature formulation predicts less heat transfer then older isothermal wall models. The effect of circumferential conduction around the tube wall is not included in their analysis. A close look at Fig. 7 of their work, partially reproduced here as Fig. 2, shows a theoretical wall temperature profile and a few measurements of surface temperature around the tube wall. In their discussion of this particular figure they state:

> "The profiles are seen to agree quite well, the main diferrences being in the rounding off of the more extreme peaks of the theoretical profile because of the circumferential conduction in the tube wall, which is of course more pronounced in those regions where the temperature gradient is high."

Nicol, et al., [18] also present theoretical curves of local heat transfer coefficients, local heat flux, and local tube surface temperature. These cases are presented for both an older isothermal wall model and an anisothermal wall model where heat can flow only radially in the tube wall.

Fujii, et al., [19] use the results of Nicol, et al., [18] for variable wall surface temperature, coupled with earlier work [20] and develop another model based upon the assumption of uniform heat flux around the tube. These authors also recognize the path of circumferential heat conduction as an important area for further work.

F. Purpose of Research

It is in this final area that the author has analyzed, with the computer, a single tube of a condenser and has included in his analysis the circumferential conduction of heat in the tube wall, a phenomenon not customarily included in condenser heat transfer analysis.

II. A SPECIFIC PROBLEM FOR STUDY

A. THE SINGLE TUBE PROBLEM

A review of prior research has indicated ideas and trends. One basic idea was that local heat transfer coefficients depend upon local temperature differences and that the shearing force depends upon these heat transfer coefficients. The trend was away from older isothermal wall models to newer variable wall temperature (anisothermal) models. The logical continuation of the trend would indicate that a wall fully capable of two dimensional heat conduction would have been better still.

Since actual tube walls can conduct heat in the circumferential direction, then a model which could account for this would be an improvement over previous models. In order to test the plethora of shear force and condensation rate theories, a model including the effect of circumferential conduction is desirable, and may prove to be essential.

B. THE PROBLEM STATEMENT

The problem was posed for the upper half of a cylindrical condenser tube with a cross-flowing vapor, that is, where the direction of the gravitational force and the direction of vapor flow where perpendicular, (See Fig. 1a). Symmetry with the other half of the tube was assumed, allowing the simplification that the ends of the half tube, where it would normally

join the other half, were adiabatic walls. The problem for solution was set up so that θ, the local temperature difference, was defined thusly:

$$\theta(r,\phi) = T_s - T(r,\phi) \tag{1}$$

While T_s may vary with pressure changes around the tube, it is assumed constant herein. The governing equation for heat transfer within the tube wall is the Laplace Equation:

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} + \frac{1}{r^2}\frac{\partial^2\theta}{\partial\phi^2} = 0 \quad , \tag{2}$$

with the following boundary conditions:

$$q_i = k_w \left(\frac{\partial\theta}{\partial r}\right)_{r_i,\phi} = h_i\,[\theta(r_i,\phi) - \theta_c]$$

$$q_o = -k_w \left(\frac{\partial\theta}{\partial r}\right)_{r_o,\phi} = h_\ell\theta_o \quad .$$

On the inside of the tube turbulent forced convection was assumed and the Dittus-Boelter correlation [21] was used to provide a heat transfer coefficient.

On the outside of the tube, the condensate flow was taken to be laminar, and heat transfer through the thin condensate layer was assumed to be purely by conduction. For such conditions the film heat transfer coefficient is given by:

$$h_\ell = \frac{k_\ell}{\delta} \tag{3}$$

The film thickness δ was calculated from the formulation due to Nicol, et al., [18] (see also Appendix A). This analysis yields the following first-order differential equation:

$$\frac{d\delta}{d\phi} = \frac{\dfrac{3\mu r_o k_\ell \theta_o}{gh_{fg}'\rho_\ell(\rho_\ell-\rho_v)} - \delta^4\sin\phi - \dfrac{3\delta^3}{2g(\rho_\ell-\rho_v)}\dfrac{d\tau_v}{d\phi}}{\dfrac{3\delta^2\tau_v}{g(\rho_\ell-\rho_v)} - 3\delta^3\cos\phi} . \tag{4}$$

The shear term, τ_v, used by Nicol, et al., [18] was one given by Schlicting [22] and is of the following form:

$$\tau_v = \frac{\frac{1}{2}\rho_v U_v^2}{\left(\frac{U_v r_o \rho_v}{\mu_v}\right)^{\frac{1}{2}}}(6.973\phi - 2.732\phi^3 + 0.292\phi^5 - 0.0183\phi^7 + 0.000043\phi^9 - 0.000115\phi^{11}). \qquad (5)$$

For the sake of comparison this author used the same shear stress model. This model calculates vapor boundary layer separation at about 108 degrees from the forward stagnation point. Thereafter, the shear stress was set to zero.

In order to integrate Eq. (4) a starting value of condensate film thickness at the stagnation point was needed. Because high velocity steam flowing horizontally normal to a horizontal tube was to be studied, $\frac{d\delta}{d\phi}$ was set equal to zero for the stagnation point ($\phi = 0$), and an approximate starting value for the condensate film thickness, δ, was found from Eqs. (4) and (5).

Once this starting value was in hand, Eq. (4) was integrated, in its entirety, around the tube using an estimate of the tube surface temperature difference, [$\theta_o = \theta(r_o, \phi)$]. The integration resulted in the local film thickness around the tube wall. Local heat transfer coefficients for the steam side were then calculated according to Eq. (3).

Using these local heat transfer coefficients Eq. (2) could then be integrated, resulting in a temperature distribution throughout the solid tube wall. With a new set of tube-wall outer surface temperatures in hand, a new set of local heat

transfer coefficients could be calculated and applied for another iteration of the Laplace equation. If temperatures converged and heat transfer balanced, then a solution was in hand.

C. THE GALERKIN FINITE ELEMENT METHOD

The purpose of this application of the Galerkin Finite Element method is to solve a steady state two dimensioanl heat conduction problem by converting the governing partial differential equation, the Laplace equations in this case, to a series of algebraic equations. Each of these algebraic equations represents the partial differential equation over a samll sub-region of the total domain called an element. The result of the simultaneous solution of these algebraic equations is to drive the integral square error of the approximate solution to zero over each element. Elements may be of different sizes and may be clustered in areas where greater accuracy is desired.

The Galerkin Finite Element method differs from the Galerkin method in that, since the algebraic equation representing the approximate solution exists over only one small element, the resultant matrix of algebraic equations for solution takes on a banded form. That is, it has zero upper and lower triangles of significant size. The resultant savings in computer storage space and computational time by using special matrix equation solvers is significant.

In this discreet approximation method the boundary conditions are applied locally to each element on the boundary of the domain. In this case linear triangular elements were used. The algebraic approximations to the solution, called basis or shape functions, were linear. The resultant approximate solution amounts to approximating a smooth three dimensional surface by a mosaic containing a large number of small triangles. Triangles size varied, small ones being used in such areas of interest as the forward stagnation point and anywhere a steep temperature gradient could be expected to exist. Larger elements were used in areas where the temperature profile was considered to be relatively unchanging. As solutions progressed, refinement of the triangular meshes highlighted and concentrated upon areas of interest.

For greater detail on both the Galerkin method and the Galerkin finite element method, the interested reader is referred to Ozisik [23] and Fairweather [24].

The formulation and computer program were tested using classical two-dimensional problems of heat conduction from Carslaw and Jaeger [25]. The first of these was a rectangle with one side at a given temperature and the other three at a specified lower temperature. The second was a rectangle with two adjoing sides adiabatic, a third side at a given temperature, and the fourth having a given heat transfer

coefficient to a medium at some lower temperature. In both cases the finite element solutions converged to exact solutions.

A further test of the program and formulation was the problem of a rectangle with two opposite sides adiabatic, a theird side at a given temperature, and the fourth side having a local heat transfer coefficient to some medium at a lower temperature. This local heat transfer coefficient was dependent upon both the local surface temperature and the position along the wall. Since this problem cannot be compared to a classical solution, any solution could only be given credence by detailed examination. It was seen that the solution converged for smaller and smaller triangle sizes, that plots of isotherms internal to the rectangle were smooth and not obviously in error, and that heat transfer into and out of the rectangle was in balance. While certainly no proof, these comparisons led to confidence in the program.

D. APPLICATION OF THE INNER BOUNDARY CONDITION

For the inside of the tube, the boundary condition of convection heat transfer, Eq. (2), can be simple represented by noting that the inside film coefficient, h_i, is given by the Dittus-Boelter correlation [21], and is a function of coolant bulk temperature and flow rate. Thus, since the thermal resistance at his interface is independent of local tube wall temperature, the resistance may be represented by a fictitious

thickness of insulating material according to the relationship:

$$R = \frac{1}{h_i A} = \frac{r_i \ln\left(\frac{r_i}{r_i - t_f}\right)}{K_f A} . \qquad (6)$$

From this, the thickness of the fictitious ring t_f, was determined and the equivalent boundary condition, that the coolant temperature existed at the inside of the fictitious ring, was imposed.

E. SOLUTION PROCEDURE

On the outside of the tube, the local heat transfer coefficients were computed all around the tube for the current value of the calculated local outside wall temperature. These local heat transfer coefficients were applied to elements having sides on the outer tube wall.

In order to converge to the proper wall temperatures and temperature-dependent heat transfer coefficients, an iterative scheme was followed wherein a new set of local heat transfer coefficients for the outside of the tube were computed from new solution temperatures. The process was repeated until temperatures at all nodal points changed less than 0.02 degrees Celsius for consecutive iterations.

Having stabilized the local temperatures throughout the tube wall, a check was made to insure that the heat transfer balanced. The total heat deposited upon the condenser tube outer wall by the condensing steam was compared to the total heat conducted into the tube wall at the outer surface and to the total heat conducted from the tube at its inner surface.

F. COMPARISON WITH PREVIOUS SOLUTIONS

The aforementioned paper of Nicol, et al., [18] provided fertile ground for comparison, but only if the test conditions could be simulated. These authors were able to achieve a given average tube outer surface temperature by varying the flowrate of the coolant and hence the internal heat transfer coefficient. In the finite element formulation this condition is obtained by varying the thickness of the aforementioned fictitious ring. In order to preclude significant circumferential conduction in the fictitious ring, the circumferential thermal conductivity of the ficticious ring was chosen to be one one-hundredth of the thermal conductivity of the tube wall.

III. RESULTS

A. TUBE WALL TEMPERATURE

The tube wall temperature predictions of the author's finite element model are shown in Fig. (3), and are seen to support the prediction of Nicol et al., [18] that circumferential heat conduction would substantially round off the theoretical temperature profile obtained by considering radial heat conduction only. It is also worthwhile to note that the maximum and minimum temperatures are less extreme than those predicted by the radial heat flow model of Nicol et al., [18] and generally agree more closely with their experimental results. While the actual differences in temperature appear small, near the separation point of the vapor flow these differences approach thirty percent.

Nicol et al., [18] also show a theoretical tube wall surface temperature profile for another average wall temperature. This profile is reproduced in Fig. 4 along with a theoretical profile developed from the author's model. As before, the steep gradients are rounded off and the overall temperature profile is less extreme.

A plot of the isotherms within the tube wall is quite revealing and is shown in Fig. (5). The direction of vapor flow and point of vapor boundary layer separation, as indicated by the thickening of the condensate layer, are shown on the

figure. The isotherms are seen to start close together near the vapor stagnation point and to spread, reflecting lower rates of heat transfer, progressively around the tube. In the vicinity of separation of the vapor boundary layer, the isotherms are seen to deviate significantly from their concentric upstream orientation. This reflects a significant amount of heat transfer circumferentially around the tube in this general vicinity. The much wider spacing of the isotherms on the back part of the tube indicates that according to this model it is an area of relatively low heat transfer rate.

1. Local Heat Transfer Coefficients

Figure 6 shows a comparison of local heat transfer coefficients around the tube wall. The isothermal wall and radial heat flow local transfer coefficients of Nicol et al., are partially reproduced. The results of the finite element model are seen to lie generally between the other two models with the exception of the vapor-separated region. In the region prior to separation, as seen in Fig. 4, the wall temperature difference of the finite element model lies between the isothermal wall case and radial heat flow case. From Eq. (4) at the stagnation point, the initial value of the film thickness is proportional to $\theta_0^{1/3}$. Therefore, a larger temperature difference will create a larger initial film thickness, and therefore a smaller heat transfer coefficient, as given by Eq. (3). It is not unexpected that this formulation and solution should predict a greater heat

transfer coefficient in the separated region than the isothermal wall model. Since there was a higher wall temperature and therefore less steam condensed in the unseparated portion of the tube in the present model, there is a thinner condensate layer in the after section of the tube. In the separated region the greater heat transfer coefficient predicted by the author's model over the radial heat flow model is not fully explained, but is no-doubt due, in part, to the assumption of symmetry in the present formulation.

2. Local Heat Flux

In still a third examination under these same conditions, Nicol et al. in their Fig. 6 present local heat flux for both the isothermal wall and radial heat flow models. These profiles are partially reproduced here in Fig. 7 along with the author's results which again, as expected, lie between the two previous models except in the separated-vapor region of the tube. It is interesting to note that the inclusion of circumferential effects generates a heat flux which is much closer to being uniform than that which is obtained with the isothermal wall model.

IV. CONCLUSIONS

The circumferential path of heat conduction has been successfully included in the solution of laminar filmwise condensation of high velocity steam on condenser tubes. The author's anisothermal fully-conducting wall model yields closer agreement to previously measured tube wall surface temperatures than a previous anisothermal wall model which allowed only radial heat flow. The maximum and minimum values of wall temperature were less extreme for the anisothermal fully conducting wall than for the anisothermal wall with only radial heat flow.

The addition of a circumferential path for heat flow results in a complicated interplay between this heat flow and heat being deposited locally by condensation and leaving in the internal cooling water. The addition of vapor velocity effects on the outside surface of the film, and especially the sudden changes arising from separation of the vapor flow result in a highly complex sequence of thermal and fluid-dynamical interactions. The methods developed herein, though still subject to comprehensive experimental verification, are adequate to predict these complex phenomena.

V. RECOMMENDATIONS

Now that a model for two-dimensional heat conduction which includes temperature-dependent local heat transfer coefficients has been developed and demonstrated, the use of this model for further study is suggested. Areas thought fruitful for further examination are both the shear stress models and the temperature-dependent condensation rate models. For shear stress models the separated vapor region or trailing area must be given closer examination since it accounts for about forty percent of the surface area of the tube and the fluid flow characteristics in this region remain relatively unknown. In the study of temperature-dependent condensation rate models, further examination of the effect of the velocity of the flowing vapor and local temperature is expected to be fruitful.

The vigorous exercise of this model through a broad range of steam-side and coolant side conditions is suggested.

The model of condensation with constant heat flux proposed by several authors [18, 20, 26], should be re-examined since circumferential heat conduction in the tube wall, when included in theanalysis, seems to yield a nearly constant heat flux distribution.

APPENDIX A

Local Rate of Change of Condensate Film Thickness

A force balance on the shaded element of Fig. 1b yields the following:

$$\tau_v r_o d\phi - \tau_\ell r_o d\phi - g(\rho_\ell - \rho_v)\cos\phi \; r_o \; (\delta - y) \; d\phi = 0$$

so that:

$$\tau_\ell = \mu \frac{\partial u}{\partial y} = \tau_v - (\rho_\ell - \rho_v) g \cos\phi \; (\delta - y) \quad .$$

Integrating:

$$u = \frac{\tau_v}{\mu} y - (\rho_\ell - \rho_v) \frac{g}{\mu} \cos\phi \; (\delta y - \frac{y^2}{2}) \quad .$$

The average velocity, $\bar{u}$ is:

$$\bar{u} = \frac{1}{\delta} \int_o^\delta u \; dy = \frac{1}{\delta} \frac{\tau_v}{\mu} \frac{\delta^2}{2} - \frac{g}{\mu} \frac{(\rho_\ell - \rho_v)}{\delta} \cos\phi \left[\frac{\delta^3}{2} - \frac{\delta^3}{6} \right] \text{, or}$$

$$\bar{u} = \frac{\tau_v \delta}{2\mu} - (\rho_\ell - \rho_v) \frac{g}{\mu} \cos\phi \; \frac{\delta^2}{3} \quad . \tag{8}$$

The mass flow rate of condensate around the tube is:

$$\dot{m}_\ell = \rho_\ell \delta \bar{u}$$

and, with Eq. (8),

$$\dot{m}_\ell = \frac{\tau_v \rho_\ell}{2\mu} \delta^2 - \frac{g\rho_\ell(\rho_\ell - \rho_\ell)}{3\mu} \cos\phi \; \delta^3 \quad .$$

The rate of change of mass flow rate with respect to angle is:

$$\frac{d\dot{m}_\ell}{d\phi} = \frac{\rho_\ell \delta^2}{2\mu} \frac{d\tau_v}{d\phi} + \frac{\rho_\ell \tau_v \delta}{\mu} \frac{d\delta}{d\phi} + \frac{g\rho_\ell(\rho_\ell - \rho_v)\delta^3 \sin\phi}{3\mu}$$

$$- \frac{g\rho_\ell(\rho_\ell - \rho_v)}{\mu} \cos\phi \; \delta^2 \frac{d\delta}{d\phi}$$

Since $d\dot{m}/d\phi$ can also be equated to the amount of steam condensing, the following relationship applies:

$$\frac{d\dot{m}_\ell}{d\phi} = \frac{r_o k_\ell \theta_{\bar{o}}}{\delta h'_{fg}}$$

where h'_{fg} is the latent heat of vaporization corrected for subcooling. By making this substitution and solving for $d\delta/d\phi$, the relationship given in Eq. (4) is obtained.

APPENDIX B: PROGRAM LISTING

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*******************************************************************
C           A FINITE ELEMENT PROGRAM USING FIRST ORDER LINEAR GALERKIN
C
C           FINITE ELEMENTS TO SOLVE TWO-DIMENSIONAL HEAT TRANSFER
C
C           PROBLEMS WITH NON-LINEAR, TEMPERATURE DEPENDENT BOUNDARY
C
C           CONDITIONS.
C
C
C
C               THE PRESENT SET UP IS FOR A CYLINDRICAL CONDENSER TUBE
C
C           WITH FILMWISE CONDENSATION ON THE OUTSIDE AND TURBULENT
C
C           FORCED CONVECTION ON THE INSIDE.
C
C
******************************************************************
C
C
C
C                    THE FOLLOWING IS  A LIST OF
C                    VARIABLE NAMES USED IN THE
C                    PROGRAM.
C
C
C
C                      VARIABLES OF THE GENERAL PROBLEM.
C
C
C
C     ATRI      THE AREA OF EACH TRIANGLE IN THE FINITE ELEMENT
C                    GRID.
C     CSUBP      VALUE OF SPECIFIC HEAT OF LIQUID WATER AT CONSTANT
C                    PRESSURE.
C     FNEEC      VALUE OF THE FORCING FUNCTION AT EACH ESSENTIAL
C                    BOUNDARY CONDITION.
C     F          A VECTOR OF RIGHT HAND SIDES FOR SOLVING THE MATRIX
C                    EQUATION RESULTING FROM THE FINITE ELEMENT
C                    FORMULATION.
C     HH         LOCAL HEAT TRANSFER COEFFICIENT.
C     HCL        LOCAL HEAT TRANSFER COEFFICIENT.
C     KORR       THE CORRESPONDENCE TABLE RELATING THE POSITIONS
C                    OF THE THREE CORNERS OF EACH TRIANGLE.
C     NAX        THE TOTAL BANDWIDTH OF THE BANDED GLOBAL MATRIX,
C                    NAX=NLC+NLC+1.
C     NCOLN      A COUNTER.
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C     NCELI    A VECTOR CONTAINING THE NUMBER OF EACH CONVECTION           VAT00490
C                     ELEMENT ON THE INSIDE OF THE DOMAIN.                  VAT00500
C     NCELC    A VECTOR CONTAINING THE NUMBER OF EACH CONVECTION           VAT00510
C                     ELEMENT ON THE OUTSIDE OF THE DOMAIN.                 VAT00520
C     NCHK     A VALUE USED TO CHECK AGREEMENT FROM ITERATION TO           VAT00530
C                     ITERATION.                                            VAT00540
C     NEBC     THE NUMBER OF EACH OF THE NODAL POINTS WHERE A              VAT00550
C                     TEMPERATURE IS SPECIFIED.                             VAT00560
C     NEL      THE TOTAL NUMBER OF ELEMENTS.                                VAT00570
C     NLC      THE NUMBER OF LOWER CO-DIAGONALS OF THE GLOBAL MATRIX       VAT00580
C                     IN BANDED STORAGE FORM.                               VAT00590
C     NNP      THE TOTAL NUMBER OF NODAL POINTS.                            VAT00600
C     NSDC     FOR EVERY ELEMENT HAVING A CONVECTION BOUNDARY, THIS        VAT00610
C                     IS THE NUMBER OF SIDES ON THE BOUNDARY.               VAT00620
C     NUC     THE NUMBER OF UPPER CO-DIAGONALS OF THE GLOBAL MATRIX        VAT00630
C                     IN BANDED STORAGE FORM.                               VAT00640
C     RHOL    THE DENSITY OF LIQUID WATER AT SATURATION CONDITIONS.        VAT00650
C     RHOV    THE DENSITY OF WATER VAPOR AT SATURATION CONDITIONS.         VAT00660
C     X       THE HORIZONTAL COORDINATES IN THE CARTESIAN COORDINATE       VAT00670
C                     SYSTEM.                                               VAT00680
C     Y       THE VERTICAL COORDINATE IN THE CARTESIAN COORDINATE          VAT00690
C                     SYSTEM.                                               VAT00700
C     XLO12   THE LENGTH OF THE SIDE OF A CONVECTION ELEMENT FROM          VAT00710
C                     LOCAL NODAL POINT  1 TO LOCAL NODAL POINT 2.          VAT00720
C     XLO23    THE LENGTH OF A SIDE OF A CONVECTION ELEMENT                VAT00730
C                     FROM LOCAL NODAL POINT 2 TO LOCAL NODAL POINT 3.      VAT00740
C     XL      WORKSPACE FOR THE LINEAR EQUATION SOLVER.                    VAT00750
C     TBAR    THE AVERAGE OF LOCAL TEMPERATURE ALONG THE CONVECTIVE        VAT00760
C                     BOUNDARY OF AN ELEMENT HAVING A CONVECTIVE            VAT00770
C                     BOUNDARY.                                             VAT00780
C     ZA     THE GLOBAL MATRIX FORMED IN THE FINITE ELEMENT METHOD,        VAT00790
C                     STORED ON BANDED STORAGE MODE.                        VAT00800
C     ZAST   A STORAGE PLACE FOR THE GLOBAL MATRIX SO THAT ONCE IT IS      VAT00810
C                     INITIALLY FORMED IT NEEDED NOT BE FORMED AGAIN FOR    VAT00820
C                     EACH SUCCESSIVE ITERATION.                            VAT00830
C     XKLIQ  THE THERMAL CONDUCTIVITY OF LIQUID WATER AT SATURATION        VAT00840
C                     CONDITIONS.                                           VAT00850
C     XKSOL  THE THERMAL CONDUCTIVITY OF THE SOLID TUBE MATERIAL.          VAT00860
C     XMUL   THE DYNAMIC VISCOSITY OF LIQUID WATER AT THE SATURATION       VAT00870
C                     CONDITIONS.                                           VAT00880
C     XMUV   THE DYNAMIC VISCOSITY OF WATER VAPOR AT THE SATURATION        VAT00890
C                     CONDITIONS.                                           VAT00900
C     XHFG   THE LATENT HEAT OF VAPORIZATION OF WATER AT THE               VAT00910
C                     SATURATION CONDITIONS.                                VAT00920
C     VELST  THE FREE STREAM VELOCITY OF THE FLOWING STEAM.                VAT00930
C                                                                          VAT00940
C                                                                          VAT00950
C                                                                          VAT00960
```

```
C                    VARIABLE NAMES ASSOSCIATED WITH                    VAT00970
C                    THE SPECIFIC GEOMETRY OF THIS                      VAT00980
C                    PROBLEM.                                           VAT00990
C                                                                       VAT01000
C                                                                       VAT01010
C                                                                       VAT01020
C     R        THE VARIOUS RADII AT WHICH POINTS WILL BE PLACED IN      VAT01030
C                    THE FINITE ELEMENT GRID.                           VAT01040
C     PHEE     THE VARIOUS ANGLES AT WHICH POINTS WILL BE PLACED IN     VAT01050
C                    THE FINITE ELEMENT GRID.                           VAT01060
C     TAU      A VECTOR OF LOCAL SHEAR FORCE VALUES, ONE FOR EACH OF    VAT01070
C                    THE CONVECTION ELEMENTS.                           VAT01080
C     DTAU     A VECTOR OF LOCAL RATE OF CHANGE OF SHEAR FORCE WITH     VAT01090
C                    RESPECT TO ANGLE PHEE FOR EACH CONVECTION ELEMENT. VAT01100
C     NBNPI    NUMBER OF BOUNDARY NODAL POINTS, INSIDE.                 VAT01110
C     NBNPO    NUMBER OF BOUNDARY NODAL POINTS, OUTSIDE.                VAT01120
C     NANG     NUMBER OF ANGLES AT WHICH NODAL POINTS ARE TO BE         VAT01130
C                  PLACED.                                              VAT01140
C     NRAD     NUMBER OF RADIALLY ORIENTED HEAT FLOW PATHS.             VAT01150
C     NEIR     THE NUMBER OF ELEMENTS IN A RADIAL ROW.                  VAT01160
C     NPIR     THE NUMBER OF NODAL POINTS IN A RADIAL ROW.              VAT01170
C     NCBCO    THE NUMBER OF OUTER CONVECTION BOUNDARY CONDITIONS.      VAT01180
C                                                                       VAT01190
C                                                                       VAT01200
      DIMENSION F(320),NCELO(40),NCELI(40),NSDC(40),HCK(600)            VAT01210
     1,TEM(320),TEAR(40),YEAR(40),HH(600)                               VAT01220
      DIMENSION KORR(600,3),ZA(320,25),R(15),PHEE(50)                   VAT01230
      DIMENSION XL(8000),ZAST(320,25),TAU(40),DTAU(40)                  VAT01240
      REAL * 8 X(320),Y(320),ATRI(600),XLO12(40),XLO23(40)              VAT01250
      DIMENSION C(10),NEBC(40),FNEBC(40),NBNPI(40),NBNPO(40)            VAT01260
      READ (5,111)NLC,NUC,NCOUN,NCHK,NCO                                VAT01270
      READ(5,99)NNP,NEL,CSLBF,PHCL,RHOV,XKLIC,XKSOL                     VAT01280
      READ(5,106)XMUL,XMUV,XHFG,VELST                                   VAT01290
106   FORMAT(2(F16.14),F16.2,F10.5)                                     VAT01300
      READ(5,120) NBC                                                   VAT01310
120   FORMAT(I5)                                                        VAT01320
      DO 146 IB=1,NBC                                                   VAT01330
      READ (5,142)NEBC(IB),FNEBC(IB)                                    VAT01340
142   FORMAT(I5,F10.5)                                                  VAT01350
146   CONTINUE                                                          VAT01360
C                                                                       VAT01370
C                 CVERT IS A SUBROUTINE WHICH READS IN VALUES OF ANGLE  VAT01380
C                                                                       VAT01390
C           FROM THE FORWARD STAGNATION POINT AND RADIUS FROM THE       VAT01400
C                                                                       VAT01410
C           CENTER OF THE TUBE AND CONVERTS THESE TO X AND Y CARTESIAN  VAT01420
C                                                                       VAT01430
C           COORDINATES.                                                VAT01440
```

```
C
C
      CALL CVERT(X,Y,R,PHEE,NNP)
C
C
C           KORRF IS A SUBROUTINE USED TO DEVELOP THE CORRESPONDENCE
C
C      TABLE IN ORDER TO CONNECT THE NODAL POINTS IN THE PROPER ORDER
C
C      TO FORM THE PROPER TRIANGULAR GRID.
C
C
      CALL KORRF(KORR,NEL)
C
C
C            GEOM IS A SUBROUTINE USED TO FIGURE THE AREA OF EACH
C
C        TRIANGULAR ELEMENT AND THE LENGTH OF ANY SIDE ALONG A CON-
C
C        VECTION BOUNDARY CONDITION.
C
C
      CALL GEOM(NNP,NEL,X,Y,KORR,ATRI,NCELO,XLO12,XLO23,
     1NCC,NSEC)
C
C
C          FORMB IS A SUBROUTINE WHICH TAKES THE X AND Y COORDINATES
C
C     AND THE AREA OF EACH TRIANGLE AND CONSTRUCTS THE LOCAL THREE BY
C
C     THREE MATRIX FOR EACH ELEMENT.  IT THEN SUPERIMPOSES EACH OF
C
C     THE VALUES FROM THE LOCAL THREE BY THREE MATRIX UPON THE PROPERLY
C
C     NUMBERED NODAL POINTS ACCORDING TO THE CORRESPONDENCE TABLE.
C
C
      CALL FORME (ATRI,NEL,NNP,X,Y,ZA,KORR,NLC,NLC)
C
C
C         ZASTC IS A SUBROUTINE WHICH STORES THE GLOBAL MATRIX, ZA,
C
C     SO THAT IT NEED NOT BE REFORMED FOR EACH SUCCESSIVE ITERATION.
C
C
      CALL ZASTC(NNP,ZA,ZAST,NLC,NLC)
C
C
```

```
C
C          TEMPS IS A SUBROUTINE WHICH DISTRIBUTES INITIAL VALUES OF
C
C     TEMPERATURE DIFFERENCE (FIRST GUESSES) AT THE CONVECTION
C
C     ASSOSCIATED NODAL POINTS SO THAT THE LOCAL TEMPERATURE DEPENDENT
C
C     HEAT TRANSFER COEFFICIENTS CAN BE CALCULATED THE FIRST TIME.
C
C
      CALL TEMPS(TEM,NBNPC,NCANPO)
C
C
C         HLOCC IS A SUBROUTINE WHICH FIGURES THE LOCAL HEAT TRANSFER
C
C     COEFFICIENTS ON THE OUTSIDE OF THE TUBE.  THIS SUBROUTINE IS
C
C     INCLUDED IN ALL ITERATIONS.
C
C
    3 CALL HLOCC(XHFG,RHOL,RHOV,XMUL,XMUV,XKLIQ,XKSOL,PHEE,R,TEM,HOK,
     1NCELC,KORR,NCO,TBAR,HH,HEEBAR,VELST,CSUBF)
      TFACT=0.
      AR=0.
      DO 324 JU=1,NCO
      TFACT=TFACT+TBAR(JU)*XLC12(JU)
      AR=AR+XLC12(JU)
  324 CONTINUE
      TAV=TFACT/AR
      WRITE(6,765)TAV
      WRITE(7,765)TAV
  765 FORMAT( ' AVERAGETEMP IS',F10.5)
C
C
C          FORMF IS A SUBROUTINE WHICH PLACES ZEROES IN THE RIGHT HAND
C
C     SIDE OF THE MATRIX EQUATION.
C
C
      CALL FORMF(F,NNP)
C
C
C          FORMCD IS A SUBROUTINE WHICH MODIFIES THE GLOBAL MATRIX FOR
C
C     THE CONVECTION BOUNDARY CONDITIONS.
C
C
      CALL FORMCD (NNP,ZA,KORR,NCELC,NSDO,XLC12,XLC23,HOK,NCO
     1,NLC,NLC)
```

```
C
C
C        MODBCE IS A SUBROUTINE WHICH MODIFIES THE GLOBAL MATRIX AND
C
C     THE FORCING FUNCTION FOR THE SPECIFIED TEMPERATURES (ESSENTIAL
C
C     BOUNDARY CONDITIONS.)
C
C
      CALL MODBCE(ZA,F,NNP,NCOUN,NEBC,NBC,FNEBC,NLC,NUC)
      MAX=NLC+NLC+1
C
C
C         LEQT1B IS A SINGLE PRECISION LINEAR EQUATION SOLVER
C
C     SPECIFICALLY PROGRAMMED TO WORK UPON BANDED MATRICES.
C
C
      CALL LEQT1B(ZA,NNP,NLC,NUC,320,F,1,1,0,XL,IER)
C
C
C        CLOSE IS A SUBROUTINE WHICH CHECKS AFTER EACH ITERATION TO
C
C     SEE HOW CLOSE THE NEW TEMPERATURE DIFFERENCES AGREE WITH THE OLD
C
C    ONES.  IF AGREEMENT IS NOT SUFFICIENT, IT REPLACES THE PRESENT
C
C     GLOBAL MATRIX WITH THE OLD, UNMODIFIED ONE AND CAUSES
C
C     THE ITERATIONS TO BEGIN AGAIN, BUT WITH THE NEW VALUES
C
C    OF LOCAL TEMPERATURE DIFFERENCE.
C
C
      CALL CLOSE(F,TEM,NNP,NENPC,NCANPO,ZA,ZAST,NCOUN,NCHK
     1,NUC,NLC)
       IF(NCOUN.EQ. 51 ) GO TO 103
      IF(NCHK .EQ. 5) GO  TO 3
      NST=1
    4 CALL HLCCC(XHFG,RHOL,RHOV,XMUL,XMUV,XKLIQ,XKSOL,PHEE,R,TEM,HOK,
     1NCELC,KORR,NCC,TBAR,HH,FEEBAR,VELST,CSUEF)
      CALL FORMF(F,NNP)
  474 FORMAT ( ' NCC FOR FORMC2 =',I5)
      CALL FORMCD (NNP,ZA,KORR,NCELC,NSDO,XLC12,
     1XLC23,HCK,NCC,NUC,NLC)
      CALL MODBCE(ZA,F,NNP,NCOUN,NEBC,NBC,FNEBC,NLC,NUC)
      CALL LEQT1B(ZA,NNP,NLC,NUC,320,F,1,1,0,XL,IER)
      DO 941 NN=1,NNP,9
```

```
      WRITE(6,202)MR,F(MR)                                               VATO2890
      WRITE(7,190) F(MR)                                                 VATO2900
190   FORMAT(F10.5)                                                      VATO2910
941   CONTINUE                                                           VATO2920
945   FORMAT(8(F10.5))                                                   VATO2930
C                                                                        VATO2940
C                                                                        VATO2950
C        HEATE IS A SUBROUTINE WHICH CHECKS TO INSURE THAT               VATO2960
C                                                                        VATO2970
C     THE TOTAL HEAT TRANSFERRED THROUGH THE TUBE WALL BALANCES.         VATO2980
C                                                                        VATO2990
C                                                                        VATO3000
      CALL HEATE(XKSOL,XKLIC,F,X,Y,NCOUN,TBAR,YBAR,HH,                   VATO3010
     1KORR,NCC,NCELC,XLO12)                                              VATO3020
C                                                                        VATO3030
C                                                                        VATO3040
C        OUTP  IS A SUBROUTINE WHICH OUTPUTS THE X AND Y COORDINATES     VATO3050
C                                                                        VATO3060
C    AND THE LOCAL TEMPERATURE DIFFERENCE, BOTH TO AN OFFLINE PRINTER    VATO3070
C                                                                        VATO3080
C    AND TO A DISC IN ORDER TO BE PLOTTED USING AVAILABLE PLOTTING       VATO3090
C                                                                        VATO3100
C    SUBROUTINES.                                                        VATO3110
C                                                                        VATO3120
C                                                                        VATO3130
      CALL OUTP(X,Y,NNP,F)                                               VATO3140
103   STOP                                                               VATO3150
111   FORMAT(I5,I5,I5,I5,I5)                                             VATO3160
98    FORMAT(I5,I5,6(F10.5))                                             VATO3170
      END                                                                VATO3180
      SUBROUTINE CVERT(X,Y,R,PHEE,NNP)                                   VATO3190
      DIMENSION R(15),PHEE(50)                                           VATO3200
      REAL * 8 X(350),Y(350)                                             VATO3210
      READ (5,108) NANG                                                  VATO3220
108   FORMAT(I5)                                                         VATO3230
      DO 110 JT=1,NANG,7                                                 VATO3240
      READ(5,111)PHEE(JT),PHEE(JT+1),PHEE(JT+2),PHEE(JT+3),PHEE(JT+4)    VATO3250
     1,PHEE(JT+5),PHEE(JT+6)                                             VATO3260
111   FORMAT(7(F8.3,2X))                                                 VATO3270
      WRITE(7,111)PHEE(JT),PHEE(JT+1),PHEE(JT+2),PHEE(JT+3),PHEE(JT+4)   VATO3280
     1,PHEE(JT+5),PHEE(JT+6)                                             VATO3290
110   CONTINUE                                                           VATO3300
      READ(5,108)NRAD                                                    VATO3310
      DO 114 JS=1,NRAD                                                   VATO3320
      READ(5,112)R(JS)                                                   VATO3330
112   FORMAT(F13.9)                                                      VATO3340
      WRITE(6,112)R(JS)                                                  VATO3350
114   CONTINUE                                                           VATO3360
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```
      DO 201 JA=1,NANG                                                  VATO3370
      S1=SIN(PHEE(JA)*3.14159265 4/180.)                                VATO3380
      C1=COS(PHEE(JA)*3.14159265 4/180.)                                VATO3390
 288  FORMAT(3X,F14.9,3X,F14.9)                                         VATO3400
      DO 202 JB=1,NRAD                                                  VATO3410
      NX=NRAD*(JA-1)+JB                                                 VATO3420
      X(NX)=R(JB)*S1                                                    VATO3430
      Y(NX)=R(JB)*C1                                                    VATO3440
 212  FORMAT(I5,3X,2(F10.5,2X))                                         VATO3450
 202  CONTINUE                                                          VATO3460
 201  CONTINUE                                                          VATO3470
      RETURN                                                            VATO3480
      END                                                               VATO3490
      SUBROUTINE KORRF(KORR,NEL)                                        VATO3500
      DIMENSION KORR(600,3)                                             VATO3510
      READ(5,206)NPATH,NEIR,NPIR                                        VATO3520
      NR=2*NEIR                                                         VATO3530
      NPR=2*NPIR                                                        VATO3540
      DO 208 JA=1,NPATH                                                 VATO3550
      DO 210 JL=1,NEIR                                                  VATO3560
      IFR=JL+(JA-1)*NR                                                  VATO3570
      IPFR=JL+(JA-1)*NPIR                                               VATO3580
      KORR(IFR,1)=IPFR+1                                                VATO3590
      KORR(IFR,2)=IPFR+NPIR+1                                           VATO3600
      KORR(IFR,3)=IPFR                                                  VATO3610
      KORR((IFR+NEIR),1)=IPFR+NPIR                                      VATO3620
      KORR((IFR+NEIR),2)=IPFR                                           VATO3630
      KORR((IFR+NEIR),3)=IPFR+NPIR+1                                    VATO3640
      IKR=IFR+NEIR                                                      VATO3650
 222  FORMAT(4(I5))                                                     VATO3660
 210  CONTINUE                                                          VATO3670
 208  CONTINUE                                                          VATO3680
      RETURN                                                            VATO3690
 206   FORMAT(3(I5))                                                    VATO3700
      END                                                               VATO3710
      SUBROUTINE GEOM(NNP,NEL,X,Y,KORR,ATRI,NCELO,XLO12,XLO23,NCO,      VATO3720
     1NSDO)                                                             VATO3730
      REAL * 8 ATRI(600),X(320),Y(320),XLO12(40),XLO23(40)              VATO3740
      DIMENSION KORR(600,3),NCELO(40),NSDO(40)                          VATO3750
      DOUBLE PRECISION PER,SPER                                         VATO3760
      DO 161 JC=1,NCO                                                   VATO3770
      READ (5,163) NCELO(JC),NSDO(JC)                                   VATO3780
 163  FORMAT(I5,I5)                                                     VATO3790
C161  WRITE(6,178) NCELO(JC),NSDO(JC)                                   VATO3800
 161  CONTINUE                                                          VATO3810
 178  FORMAT(6X,I5,10X,I5)                                              VATO3820
      DO 122 JB=1,NEL                                                   VATO3830
      XL12=DSQRT(((X(KORR(JB,1))-X(KORR(JB,2)))**2)+((Y(KORR(JB,1))-    VATO3840
```

```
     1Y(KCRR(JE,2)))**2))                                               VAT03850
      XL23=DSQRT(((X(KORR(JB,2))-X(KCRR(JB,3)))**2)+((Y(KCRR(JE,2))-    VAT03860
     1Y(KCRR(JE,3)))**2))                                               VAT03870
      XL31=DSQRT(((X(KCRR(JB,3))-X(KCRR(JB,1)))**2)+((Y(KCRR(JE,3))-    VAT03880
     1Y(KCRR(JE,1)))**2))                                               VAT03890
      IF(JE .LT. 540) GO TO 17                                          VAT03900
  431 FORMAT(3(F20.10))                                                 VAT03910
 17   PER=XL12+XL23+XL31                                                VAT03920
      SPER=PER*.5                                                       VAT03930
      ATRI(JE)=DSQRT(SPER*(SPER-XL12)*(SPER-XL23)*(SPER-XL31))          VAT03940
      DO 170 JC=1,NCO                                                   VAT03950
      IF(NCELC(JC) .NE. JB) GO TO 170                                   VAT03960
      XLC12(JC)=XL12                                                    VAT03970
      XLC23(JC)=XL23                                                    VAT03980
170   CONTINUE                                                          VAT03990
      IF(JE .LT. 540) GO TO 122                                         VAT04000
122    CONTINUE                                                         VAT04010
388   FORMAT( 'NCO= ',I5)                                               VAT04020
      RETURN                                                            VAT04030
121   FORMAT(4(I5))                                                     VAT04040
123   FORMAT(I5,2X,F18.14)                                              VAT04050
      END                                                               VAT04060
      SUBROUTINE FORMB (ATRI,NEL,NNP,X,Y,ZA,KCRR,NLC,NUC)               VAT04070
      DIMENSION KCRR(600,3),ZA(320,25)                                  VAT04080
      REAL * 8 ATRI(600),X(320),Y(320),A(3,3)                           VAT04090
      DOUBLE PRECISION B1,B2,B3,C1,C2,C3,ATR4                           VAT04100
      NAX=NLC+NLC+1                                                     VAT04110
      DO 170 KA=1,NNP                                                   VAT04120
      DO 171 KB=1,NAX                                                   VAT04130
171   ZA(KA,KB)=0.                                                      VAT04140
170   CONTINUE                                                          VAT04150
      DO 130 JC=1,NEL                                                   VAT04160
      B1=Y(KCRR(JC,2))-Y(KCRR(JC,3))                                    VAT04170
      B2=Y(KCRR(JC,3))-Y(KCRR(JC,1))                                    VAT04180
      B3=Y(KCRR(JC,1))-Y(KCRR(JC,2))                                    VAT04190
      C1=X(KCRR(JC,3))-X(KCRR(JC,2))                                    VAT04200
      C2=X(KCRR(JC,1))-X(KCRR(JC,3))                                    VAT04210
      C3=X(KCRR(JC,2))-X(KCRR(JC,1))                                    VAT04220
      ATR4=ATRI(JC)*4.                                                  VAT04230
      KC=JC/8                                                           VAT04240
      KD=KC*8                                                           VAT04250
      IF(KD .EQ. JC) ATR4=ATR4*200.                                     VAT04260
      WRITE(6,555)ATR4                                                  VAT04270
555   FORMAT( F20.15)                                                   VAT04280
      A(1,1)=(B1*B1+C1*C1)/ATR4                                         VAT04290
      A(1,2)=(B1*B2+C1*C2)/ATR4                                         VAT04300
      A(1,3)=(B1*B3+C1*C3)/ATR4                                         VAT04310
      A(2,2)=(B2*B2+C2*C2)/ATR4                                         VAT04320
```

```
      A(2,3)=(B2*B3+C2*C3)/ATR4                                         VATO4330
      A(3,3)=(B3*B3+C3*C3)/ATR4                                         VATO4340
      ZA(KORR(JC,1),(NLC+1))=ZA(KORR(JC,1),(NLC+1))+A(1,1)              VATO4350
      ZA(KORR(JC,1),(KORR(JC,2)-KORR(JC,1)+NLC+1))=ZA(KORR(JC,1),(KORR  VATO4360
     1(JC,2)-KORR(JC,1)+NLC+1))+A(1,2)                                  VATO4370
      ZA(KORR(JC,1),(KORR(JC,3)-KORR(JC,1)+NLC+1))=ZA(KORR(JC,1),(KORR  VATO4380
     1(JC,3)-KORR(JC,1)+NLC+1))+A(1,3)                                  VATO4390
      ZA(KORR(JC,2),(NLC+1))=ZA(KORR(JC,2),(NLC+1))+A(2,2)              VATO4400
      ZA(KORR(JC,2),(KORR(JC,1)-KORR(JC,2)+NLC+1))=ZA(KORR(JC,2),(KORR  VATO4410
     1(JC,1)-KORR(JC,2)+NLC+1))+A(1,2)                                  VATO4420
      ZA(KORR(JC,3),(KORR(JC,1)-KORR(JC,3)+NLC+1))=ZA(KORR(JC,3),(KORR  VATO4430
     1(JC,1)-KORR(JC,3)+NLC+1))+A(1,3)                                  VATO4440
      ZA(KORR(JC,3),(NLC+1))=ZA(KORR(JC,3),(NLC+1))+A(3,3)              VATO4450
      ZA(KORR(JC,2),(KORR(JC,3)-KORR(JC,2)+NLC+1))=ZA(KORR(JC,2),(KORR  VATO4460
     1(JC,3)-KORR(JC,2)+NLC+1))+A(2,3)                                  VATO4470
  130 ZA(KORR(JC,3),(KORR(JC,2)-KORR(JC,3)+NLC+1))=ZA(KORR(JC,3),(KORR  VATO4480
     1(JC,2)-KORR(JC,3)+NLC+1))+A(2,3)                                  VATO4490
      RETURN                                                            VATO4500
      END                                                               VATO4510
      SUBROUTINE ZASTO(NNP,ZA,ZAST,NLC,NLC)                             VATO4520
      DIMENSION ZA(320,25),ZAST(320,25)                                 VATO4530
      NAX=NLC+NLC+1                                                     VATO4540
      DO 83 NY=1,NNP                                                    VATO4550
      DO 84 NZ=1,NAX                                                    VATO4560
   84 ZAST(NY,NZ)=ZA(NY,NZ)                                             VATO4570
   83 CONTINUE                                                          VATO4580
  601 CONTINUE                                                          VATO4590
      RETURN                                                            VATO4600
      END                                                               VATO4610
      SUBROUTINE FORMF(F,NNP)                                           VATO4620
      DIMENSION F(320)                                                  VATO4630
      DO 177 KX=1,NNP                                                   VATO4640
  177 F(KX)=0.                                                          VATO4650
      RETURN                                                            VATO4660
      END                                                               VATO4670
      SUBROUTINE TEMDS(TEM,NBNPO,NCANPO)                                VATO4680
      DIMENSION TEM(320),NBNPO(40)                                      VATO4690
      READ (5,301)NCANPO                                                VATO4700
  301 FORMAT(I5)                                                        VATO4710
      DO 305 NR=1,NCANPO                                                VATO4720
      READ(5,302) NBNPO(NR),TEM(NBNPO(NR))                              VATO4730
  305 CONTINUE                                                          VATO4740
  302 FORMAT(I5,F10.5)                                                  VATO4750
      RETURN                                                            VATO4760
      END                                                               VATO4770
      SUBROUTINE FLOCO(XHFG,RHOL,RHOV,XMUL,XMUV,XKLIQ,XKSOL,PHEE,R,     VATO4780
     1TEM,HCK,NCELC,KORR,NCC,TEAR,HH,FEEBAR,VELST,CSUBF)               VATO4790
      DIMENSION TEM(320),HCK(600),NBNP(40), NCEL(40),TAU(40)            VATO4800
```

```
      DIMENSION PHEE(50),R(15),NCELO(40),DTAU(40)                       VATO4810
     1,KORR(600,3),TBAR(40),HH(600),FEEBAR(40)                          VATO4820
      ROUT=R(1)                                                         VATO4830
  357 FORMAT( F13.2,2(F10.5),2(F20.9),4(F10.5))                         VATO4840
      NCAT=0                                                            VATO4850
      PHHH=0.                                                           VATO4860
      DO 310 NL=1,NCO                                                   VATO4870
      TBAR(NL)=(TEM(KORR(NCELO(NL),1))+TEM(KORR(NCELO(NL),2)))/2.       VATO4880
      IF (NCAT .NE. 0) GO TO 305                                        VATO4890
      DELO=(((XMUL*ROUT*XKLIC*SQRT(VELST*ROUT*RHOV/XMUV)                VATO4900
     1*TBAR(NL))/(1.7432*RHOL*RHOV*VELST*VELST*(XHFG+3.54*CSUBP         VATO4910
     1*TBAR(NL)))))**.3333                                              VATO4920
      WRITE(6,318) DELO                                                 VATO4930
  318 FORMAT( 'DELO TO START = ',F14.9)                                 VATO4940
  305 NCAT=NCAT+1                                                       VATO4950
                                                                        VATO4960
      FEEBAR(NL)=(PHEE(NL)+PHEE(NL+1))*3.141592654/(180.*2.)            VATO4970
      DELFEE=ABS(PHEE(NL)-PHEE(NL+1))*3.141592654/180.                  VATO4980
      TAU(NL)=.5*RHOV*VELST*VELST/SQRT(VELST*RHOV*ROUT/XMUV)            VATO4990
     1*(6.973*FEEBAR(NL)-2.732*FEEBAR(NL)**3+.292*FEEBAR                VATO5000
     1(NL)**5-.0163*FEEBAR(NL)**7+.000043*FEEBAR(NL)**9-.000115*        VATO5010
     1FEEBAR(NL)**11)                                                   VATO5020
      DTAU(NL)=.5*RHOV*VELST*VELST/SQRT(VELST*RHOV*ROUT/XMUV)           VATO5030
     1*(6.973-8.196*FEEBAR(NL)**2+1.46*FEEBAR(NL)**4                    VATO5040
     1-.1281*FEEBAR(NL)**6+.00387*FEEBAR(NL)**8-.001265*FEEBAR(NL)      VATO5050
     1**10)                                                             VATO5060
      IF(FEEBAR(NL) .GT. 1.884) TAU(NL)=0.                              VATO5070
      IF(FEEBAR(NL) .GT. 1.884) DTAU(NL)=0.                             VATO5080
      WRITE(6,125) NL,TAU(NL),DTAU(NL)                                  VATO5090
  125 FORMAT( I5,'SHEAR=',F10.5,' D SHEAR= ',F10.5)                     VATO5100
      IF(FEEBAR(NL) .GT. 1.884) GO TO 213                               VATO5110
      DLPLUS=(((ROUT*XKLIC*TBAR(NL)*XMUL/(DELO**2*(XHFG+3.54*CSUBP*TBA  VATO5120
     1R(NL))*RHOL*TAU(NL))))-((DELO*DTAU(NL))/(2.*TAU(NL))))*DELFEE     VATO5130
  213 FACT1=(3.*XMUL*ROUT*XKLIC*TBAR(NL))/(9.81*RHOL*(RHOL-RHOV)        VATO5140
     1*(XHFG+3.54*CSUBP*TBAR(NL)))                                      VATO5150
      FACT2=SIN(FEEBAR(NL))*DELO**4                                     VATO5160
      FACT3=3.*DELO**3*DTAU(NL)/(2.*9.81*(RHOL-RHOV))                   VATO5170
      FACT4=3.*TAU(NL)*DELO**2/(9.81*(RHOL-RHOV))                       VATO5180
      FACT5=3.*COS(FEEBAR(NL))*DELO**3                                  VATO5190
      DELAD=((FACT1-FACT2-FACT3)/(FACT4-FACT5))*DELFEE                  VATO5200
      WRITE(6,288) DELAD,DLPLUS                                         VATO5210
  288 FORMAT( ' DELAD=',F14.9, ' DLPLUS = ',F14.9)                      VATO5220
      DELO=DELAD/2.+DELO                                                VATO5230
      HH(NCELO(NL))=XKLIC/DELO                                          VATO5240
      PHHH=PHHH+DELFEE*HH(NCELO(NL))                                    VATO5250
      HCK(NCELO(NL))=HH(NCELO(NL))/XKSOL                                VATO5260
      ANGBR=FEEBAR(NL)*180./3.141592654                                 VATO5270
      WRITE(6,322)NCELO(NL),TBAR(NL),ANGBR,HCK(NCELO(NL)),              VATO5280
```

```
     1HH(NCELO(NL)),DELC                                                VATO5290
      DELC=DELAC/2.+DELC                                                VATO5300
 322  FORMAT(I5,5(F20.9,2X))                                            VATO5310
 310  CONTINUE                                                          VATO5320
      HAWAV=HHHH/3.141592654                                            VATO5330
      WRITE(6,343)HAWAV                                                 VATO5340
 343  FORMAT( ' AREA WEIGHTED AVERAGE H IS: ',F12.3)                    VATO5350
      RETURN                                                            VATO5360
 111  FORMAT(I5,I5)                                                     VATO5370
      END                                                               VATO5380
      SUBROUTINE FORMOD (NNF,ZA,KORR,NCELO,NSOO,XLO12,                  VATO5390
     1XLO23,HOK,NCO,NUC,NLC)                                            VATO5400
      DIMENSION ZA(320,25),KORR(600,3),NCELO(40),NSOO(40),HOK(600)      VATO5410
      REAL * 8 XLO12(40),XLO23(40)                                      VATO5420
 222  FORMAT ( ' IN FORMOD ' ,4(I5))                                    VATO5430
      DO 185 JR=1,NCO                                                   VATO5440
 486  FORMAT(6X,I5,2(F14.5))                                            VATO5450
      XNUM=HOK(NCELO(JR))*XLO12(JR)/3.                                  VATO5460
      IF(NSOO(JR) .EQ. 2) GO TO 185                                     VATO5470
      ZA(KORR(NCELO(JR),1),(NLC+1))=ZA(KORR(NCELO(JR),1),(NLC+1))+XNUM  VATO5480
      ZA(KORR(NCELO(JR),1),(KORR(NCELO(JR),2)-KORR(NCELO(JR),1)+NLC+1))=VATO5490
     1ZA(KORR(NCELO(JR),1),(KORR(NCELO(JR),2)-KORR(NCELO(JR),1)+NLC+1)) VATO5500
     1+XNUM/2.                                                          VATO5510
      ZA(KORR(NCELO(JR),2),(NLC+1))=ZA(KORR(NCELO(JR),2),(NLC+1))+XNUM  VATO5520
      ZA(KORR(NCELO(JR),2),(KORR(NCELO(JR),1)-KORR(NCELO(JR),2)+NLC+1))=VATO5530
     1ZA(KORR(NCELO(JR),2),(KORR(NCELO(JR),1)-KORR(NCELO(JR),2)+NLC+1)) VATO5540
     1+XNUM/2.                                                          VATO5550
 185  CONTINUE                                                          VATO5560
      RETURN                                                            VATO5570
      END                                                               VATO5580
      SUBROUTINE MODBCE (ZA,F,NNP,NCCUN,NEBC,NBC,FNEBC,NLC,NUC)         VATO5590
      DIMENSION ZA(320,25),F(320),NEBC(40),FNEBC(40)                    VATO5600
      IF(NCCUN .EQ. 0) GO TO 801                                        VATO5610
 801  WRITE(6,788) NCCUN                                                VATO5620
 788  FORMAT( 20X,I5)                                                   VATO5630
      NAX=NLC+NLC+1                                                     VATO5640
      DO 148 IT=1,NBC                                                   VATO5650
      DO 144 IC=1,NAX                                                   VATO5660
 144  ZA(NEBC(IT),IC)=0.                                                VATO5670
      ZA(NEBC(IT),(NLC+1))=1.                                           VATO5680
      F(NEBC(IT))=FNEBC(IT)                                             VATO5690
 148  CONTINUE                                                          VATO5700
 243  FORMAT(F10.5)                                                     VATO5710
      RETURN                                                            VATO5720
      END                                                               VATO5730
      SUBROUTINE CLOSE(F,TEM,NNP,NBNPO,NCANPO,ZA,ZAST,NCCUN,NCHK        VATO5740
     1,NLC,NUC)                                                         VATO5750
      DIMENSION F(320),TEM(320),NBNPO(40),ZA(320,25),ZAST(320,25)       VATO5760
```

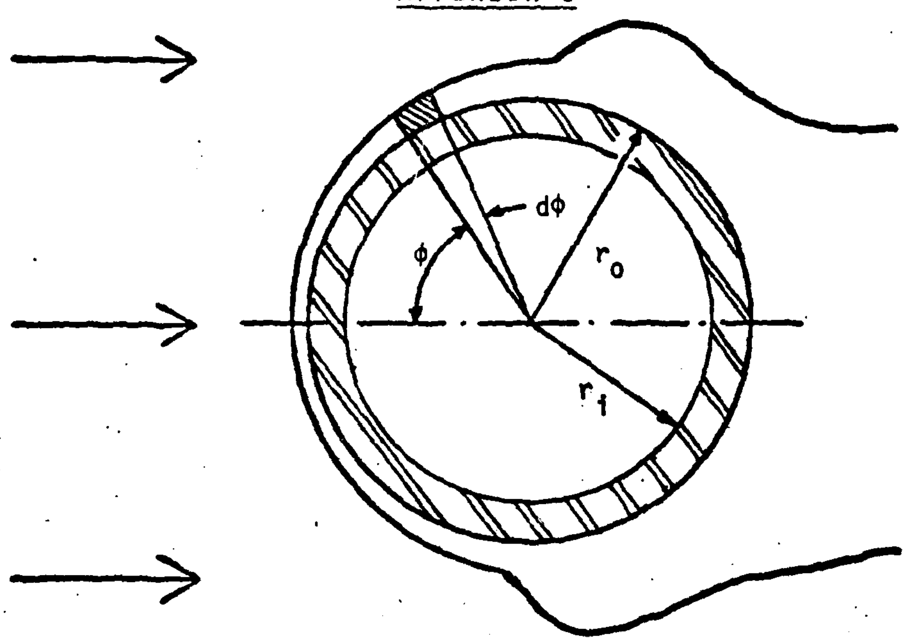
```
      DO 321 II=1,NNP
322   FORMAT(2(F10.5))
321   CONTINUE
      DO 234 IN=1,NCANFC
233   FORMAT(I5)
234   CONTINUE
      NCHK=0
756   FORMAT( 'IN CLOSE' )
      DO 709 JR=1,NCANFC
      JT=NCANFC-JR+1
      IF(ABS(F(NBNFC(JT))-TEM(NBNPC(JT))) .LT. .02) GO TO  709
      TEM(NBNFC(JT))=(TEM(NBNFC(JT))+F(NBNFC(JT)))/2.
      NCHK=5
709   CONTINUE
      DO 836 JC=1,NNP
836   TEM(JC)=F(JC)
904   NCOUN=NCOUN+1
      NAX=NLC+NLC+1
      DO 690 M1=1,NNP
      DO 691 M2=1,NAX
691   ZA(M1,M2)=ZAST(M1,M2)
690   CONTINUE
C      WRITE(6,251)NCOUN
251   FORMAT( 15X,I5)
108   RETURN
      END
      SUBROUTINE OUTP(X,Y,NNP,F,FNEBC)
      REAL * 8 X(320),Y(320)
      DIMENSION F(320),FNEBC(40)
      WRITE(6,158)
      DO 163 IL=1,NNP
      IF (F(IL) .EQ.  45.) GO TO 163
      WRITE(6,162)X(IL),Y(IL),F(IL)
      WRITE(7,162)X(IL),Y(IL),F(IL)
163   CONTINUE
158   FORMAT(' X-DIST       Y-DIST      FEM SOLN')
162   FORMAT(3(F11.5))
      RETURN
      END
772   SUBROUTINE HEATB(XKSOL,XKLIQ,F,X,Y,NCOLN,TBAR,YBAR,HH,
     1KORR,NCC,NCELC,XLC12)
      DIMENSION F(320),TBAR(40),YBAR(40),NCELC(40),
     1FH(600),KCRR(320,3),NCBOF(40),NOBAP(40),NOCCP(40),NCCAP(40)
     1,AREAI(40),AREAO(40),CIN(40),QCUT(40),CCCNV(40),CCNA(40)
      REAL * 8 XLC12(40),X(320),Y(320)
      READ(5,861) NECP
861   FORMAT(I5)
      DO 860 J=1,NECP
```

VAT0577C
VAT0578C
VAT0579C
VAT0580C
VAT0581C
VAT0582C
VAT0583C
VAT0584C
VAT0585C
VAT0586C
VAT0587C
VAT0588C
VAT0589C
VAT0590C
VAT0591C
VAT0592C
VAT0593C
VAT0594C
VAT0595C
VAT0596C
VAT0597C
VAT0598C
VAT0599C
VAT0600C
VAT0601C
VAT0602C
VAT0603C
VAT0604C
VAT0605C
VAT0606C
VAT0607C
VAT0608C
VAT0609C
VAT0610C
VAT0611C
VAT0612C
VAT0613C
VAT0614C
VAT0615C
VAT0616C
VAT0617C
VAT0618C
VAT0619C
VAT0620C
VAT0621C
VAT0622C
VAT0623C
VAT0624C

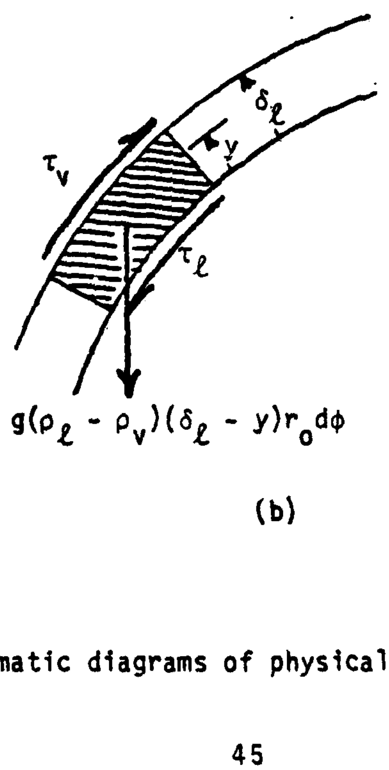
```
      READ (5,862) NOBOP(J),NOBAP(J)                                      VATO6250
  860 CONTINUE                                                            VATO6260
  862 FORMAT(I5,I5)                                                       VATO6270
  866 ATOTI=0.                                                            VATO6280
      CTOTI=0.                                                            VATO6290
      DO 864  JA=1,NCO                                                    VATO6300
      DF=(F(NOBOP(JA))+F(NOBOP(JA+1)))/2.-(F(NOBAP(JA))+F(NOBAP(JA        VATO6310
     1+1)))/2.                                                            VATO6320
       DIST=DSQRT((X(NOBOP(JA))-X(NOBAP(JA)))**2+(Y(NOBOP(JA))-Y(NOBAP    VATO6330
     1(JA)))**2)                                                          VATO6340
  911 FORMAT(3X,2(F10.7))                                                 VATO6350
      IF(JA .GT. 1) GO TO 870                                             VATO6360
      AREAI(JA)=.5*(DSQRT((X(NOBOP(JA))-X(NOBOP(JA+1)))**2                VATO6370
     1+(Y(NOBOP(JA))-Y(NOBOP(JA+1)))**2))                                 VATO6380
      GO TO 872                                                           VATO6390
  870  IF(JA .EQ. NOBOP) GO TO 871                                        VATO6400
      AREAI(JA)=.5*(DSQRT((X(NOBOP(JA))-X(NOBOP(JA+1)))**2                VATO6410
     1+(Y(NOBOP(JA))-Y(NOBOP(JA+1)))**2))                                 VATO6420
     1+.5*(DSQRT((X(NOBOP(JA-1))-X(NOBOP(JA)))**2                         VATO6430
     1+(Y(NOBOP(JA-1))-Y(NOBOP(JA)))**2))                                 VATO6440
      GO TO 872                                                           VATO6450
  871  AREAI(JA)=.5*(DSQRT((X(NOBOP(JA-1))-X(NOBOP(JA)))**2               VATO6460
     1+(Y(NOBOP(JA-1))-Y(NOBOP(JA)))**2))                                 VATO6470
  872 CIN(JA)=XKSCL*AREAI(JA)*DF/DIST                                     VATO6480
      CTOTI=CTOTI+CIN(JA)                                                 VATO6490
      ATOTI=ATOTI+AREAI(JA)                                               VATO6500
  864 CONTINUE                                                            VATO6510
      READ(5,941) NCOP                                                    VATO6520
  941 FORMAT(I5)                                                          VATO6530
      DO 920 J=1,NCOP                                                     VATO6540
      READ (5,942) NOCOP(J),NOCAP(J)                                      VATO6550
  920 CONTINUE                                                            VATO6560
  942 FORMAT(I5,I5)                                                       VATO6570
  946 ATOTO=0.                                                            VATO6580
      CTOTO=0.                                                            VATO6590
      ATTOT=0.                                                            VATO6600
      DO 944  JA=1,NCO                                                    VATO6610
      DF=(F(NOCAP(JA))+F(NOCAP(JA+1)))/2.-(F(NOCOP(JA))+F(NOCOP(JA        VATO6620
     1+1)))/2.                                                            VATO6630
      DIST=DSQRT((X(NOCOP(JA))-X(NOCAP(JA)))**2+(Y(NOCOP(JA))-Y(NOCAP(JA  VATO6640
     1)))**2)                                                             VATO6650
  921 FORMAT(3X,2(F10.7))                                                 VATO6660
      IF(JA .GT. 1) GO TO 950                                             VATO6670
      AREAO(JA)=.5*(DSQRT((X(NOCOP(JA))-X(NOCOP(JA+1)))**2                VATO6680
     1+(Y(NOCOP(JA))-Y(NOCOP(JA+1)))**2))                                 VATO6690
      GO TO 952                                                           VATO6700
  950  IF(JA .EQ. NCOP) GO TO 951                                         VATO6710
      AREAO(JA)=.5*(DSQRT((X(NOCOP(JA))-X(NOCOP(JA+1)))**2                VATO6720
```

```
     1+(Y(NCCCF(JA))-Y(NCCCF(JA+1)))**2))                                VAT06730
     1+.5*(DSCRT((X(NOCCF(JA-1))-X(NCCOP(JA)))**2                        VAT06740
     1+(Y(NCCCF(JA-1))-Y(NCCCF(JA)))**2))                                VAT06750
      GC TC 952                                                          VAT06760
  951  AREAC(JA)=.5*(DSCRT((X(NOCCF(JA-1))-X(NOCOF(JA)))**2              VAT06770
     1+(Y(NCCCF(JA-1))-Y(NCCCP(JA)))**2))                                VAT06780
  952 COLT(JA)=XKSCL*AREAC(JA)*CF/CIST                                   VAT06790
      CTCTC=CTCTC+CCLT(JA)                                               VAT06800
      ATCTC=ATCTC+AREAO(JA)                                              VAT06810
      ATTCT=AREAC(JA)*TBAR(JA)+ATTCT                                     VAT06820
  944 CONTINUE                                                           VAT06830
      ATATC=C.                                                           VAT06840
      CTCTC=C.                                                           VAT06850
      CO 88C JB=1,NCO                                                    VAT06860
      CCCNV(JB)=FF(NCELO(JB))*XLO12(JB)*TBAR(JB)                         VAT06870
      CCNA(JB)=FF(NCELC(JB))*TBAR(JB)                                    VAT06880
      ATCTC=ATCTC+XLO12(JB)                                              VAT06890
      CTCTC=CTCTC+CCONV(JB)                                              VAT06900
  88C CCNTINUE                                                           VAT06910
      WRITE(6,879)                                                       VAT06920
  879 FCRMAT( '    AREA CLT      Q CCNC OUT      AREA IN     Q CCNC IN   VAT06930
     1AREA CCNV      Q CONCENSEC        LOCAL FLUX ' )                   VAT06940
      CC 878 JC=1,NCO                                                    VAT06950
      WRITE(6,877)AREAI(JC),CIN(JC),AREAO(JC),CCUT(JD),XLO12(JC),QCONV   VAT06960
     1(JC),CCNA(JC)                                                      VAT06970
  878 CCNTINUE                                                           VAT06980
  877 FORMAT(6(F12.6,1X),F13.2)                                          VAT06990
      WRITE(6,882)                                                       VAT07000
  882 FCRMAT( '                              TCTALS ' )                  VAT07010
      WRITE(6,879)                                                       VAT07020
      WRITE(6,877) ATOTI,CTCTI,ATOTO,QTOTO,ATCTC,CTCTC                   VAT07030
      TAVG=ATTCT/ATOTO                                                   VAT07040
      WRITE(6,400)TAVG                                                   VAT07050
      WRITE(7,400)TAVG                                                   VAT07060
  400 FORMAT( 'AVERAGE WALL TEMF = ',F10.5)                              VAT07070
      RETURN                                                             VAT07080
      END                                                                VAT07090
```

APPENDIX C



(a)



(b)

Figure 1. Schematic diagrams of physical model.

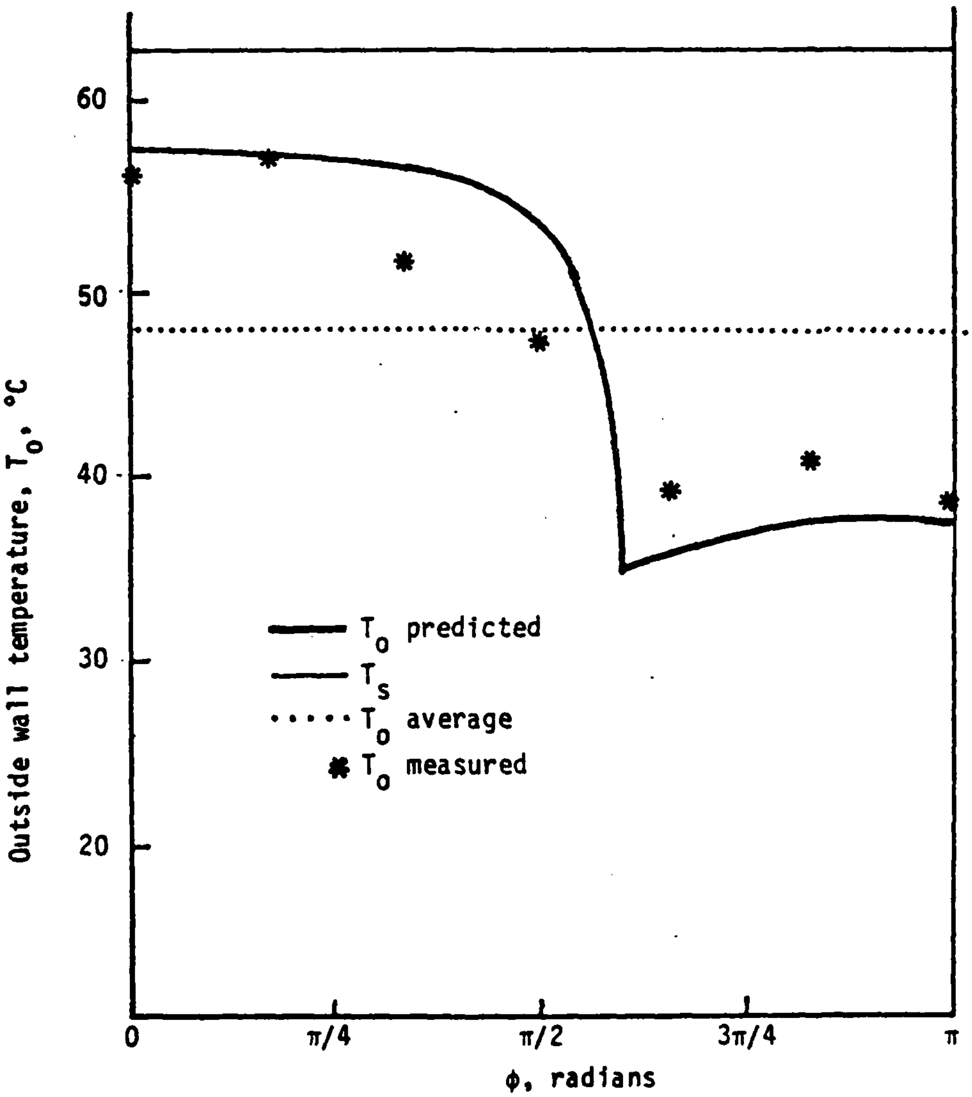


Figure 2. Predicted and measured T_o versus angle from stagnation point [18].

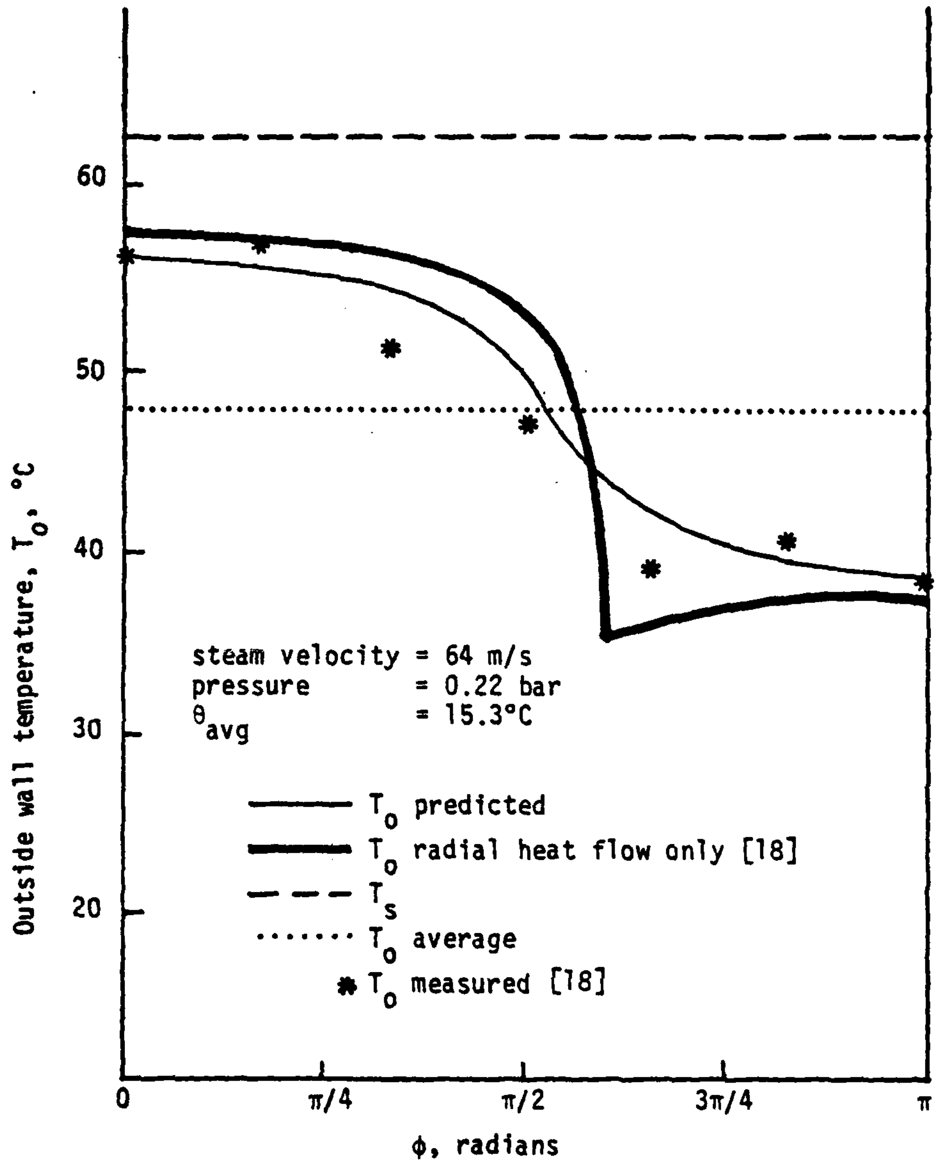


Figure 3. Predicted and measured T_o versus angle from forward stagnation point.

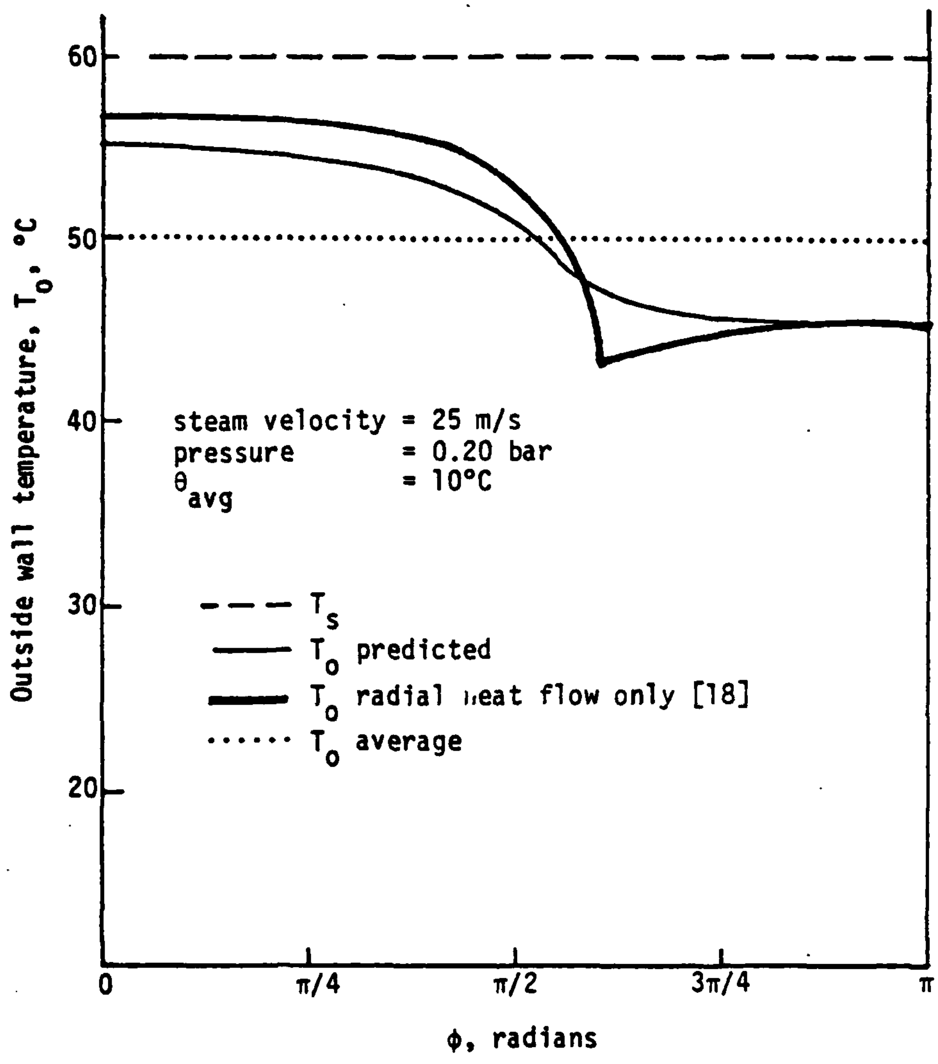


Figure 4. Predicted T_o versus angle from forward stagnation point.

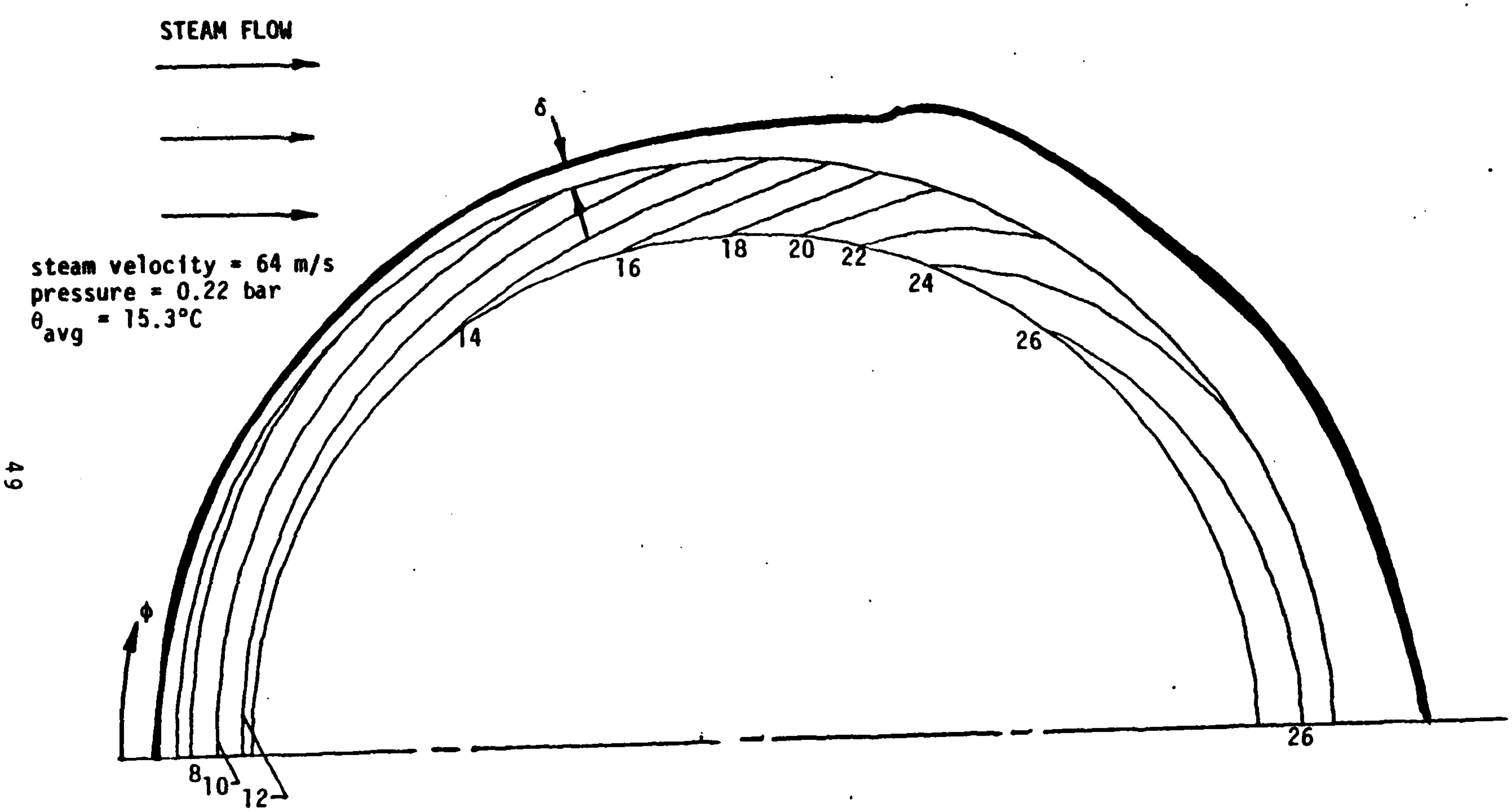


Figure 5. Isotherms (in degrees Celsius) of θ inside tube wall for top half of tube. Thickness of condensate film is shown with a magnification of 25 times.

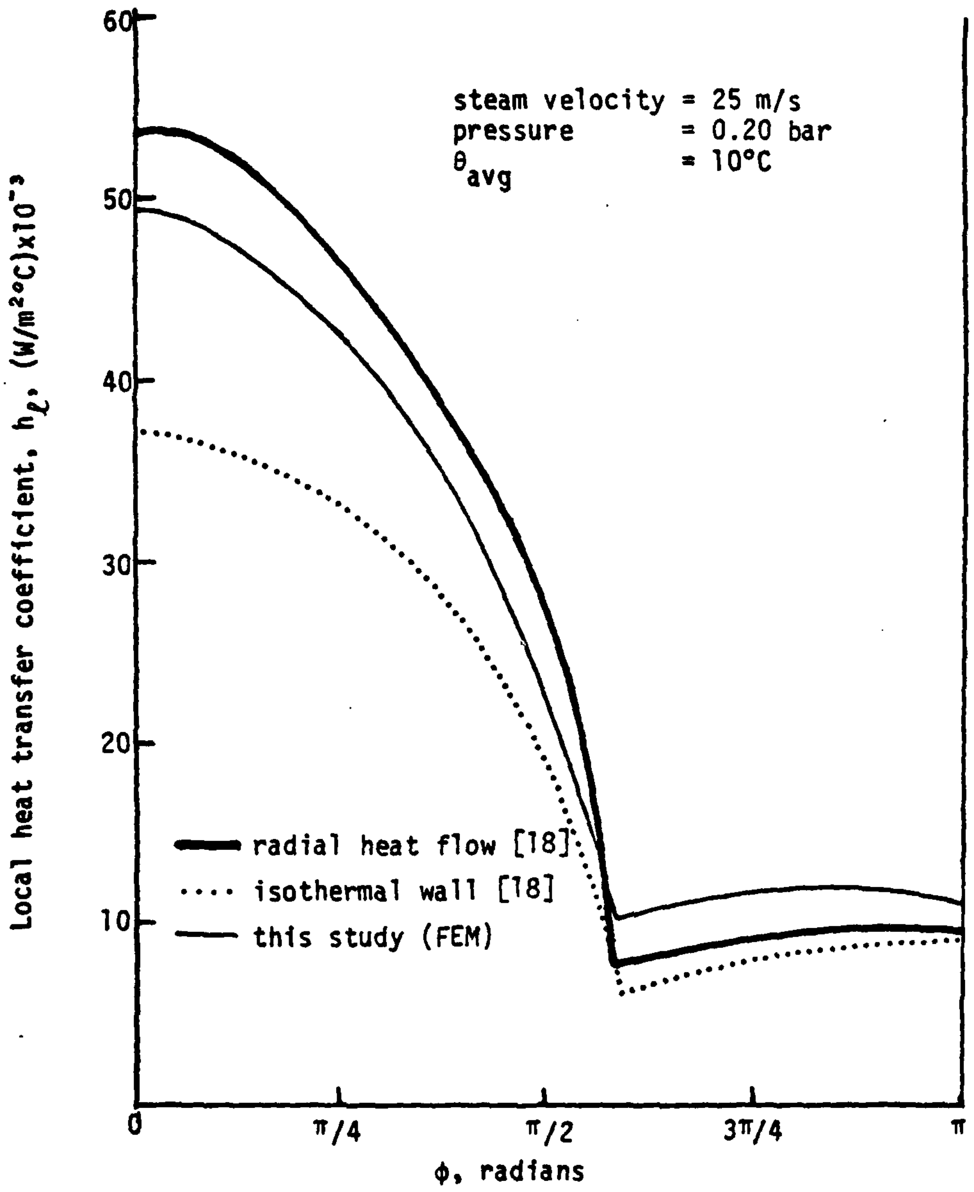


Figure 6. Predicted local heat transfer coefficient versus angle from forward stagnation point.

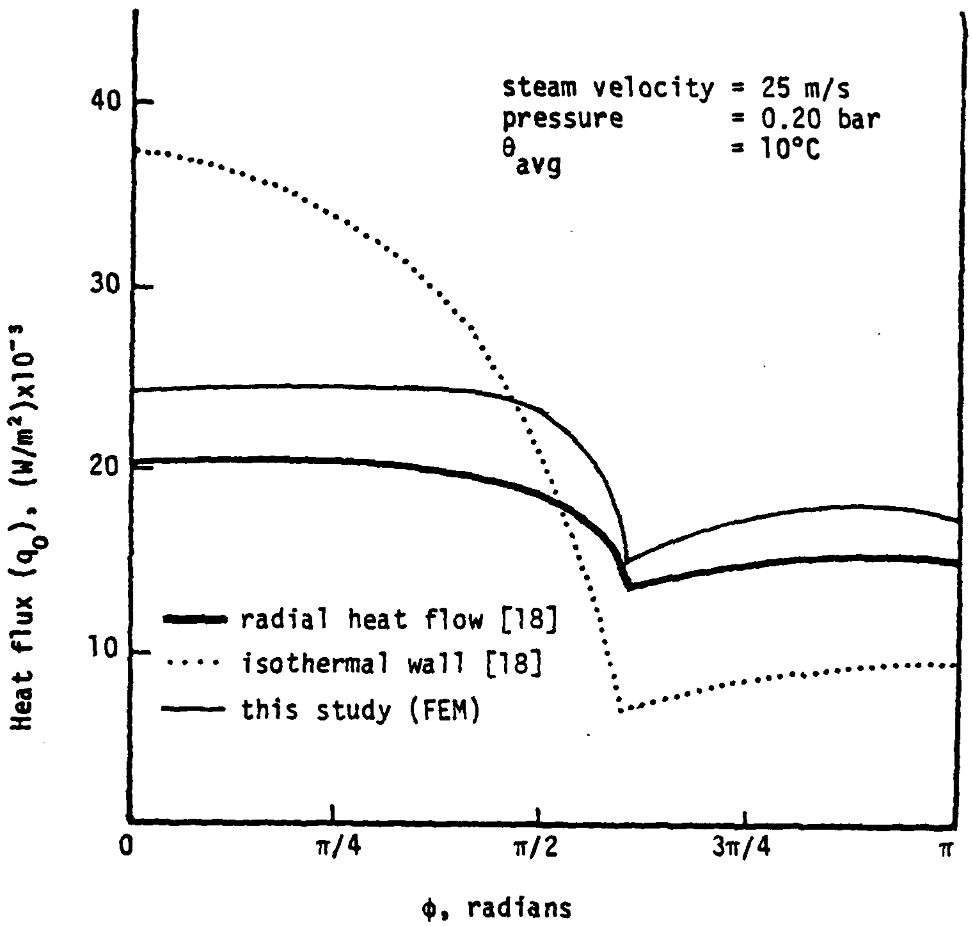


Figure 7. Predicted local heat flux versus angle from forward stagnation point.

LIST OF REFERENCES

1. Standards for Steam Surface Condensers, 6th ed., Heat Exchange Institute, 1970.

2. Standards of Tubular Exchanger Manufacturers Association, 4th ed., Tubular Exchanger Manufacturers Association, Inc., 1959.

3. Department of the Navy, Design Data Sheet Section DOS4601-1, Steam Condensers, 15 October 1953.

4. Collier, J. G. and Wallis, G. B., Two Phase Flow and Heat Transfer, lecture notes presented for a summer course, July 24 - August 4, 1967, Stanford, California, Volume 4, pp 1210 - 1215, 1967.

5. Rohsenow, W. M., Webber, J. H., and Ling, A. T., "Effect of Vapor Velocity on Laminar and Turbulent - Film Condensation," Trans. ASME, V. 78. pp 1637 - 43, 1956.

6. Sparrow, E. M. and Gregg, J. L., "A Boundary Layer Treatment of Laminar Film Condensation," Trans. ASME, V. 81C, pp 13 - 18, 1959.

7. Koh, J. C. Y., Sparrow, E. M., and Hartnett, J. P., "The Two-Phase Boundary Layer in Laminar Film Condensation," Int. J. Heat Mass Transfer, V. 2, pp 69 - 82, 1961.

8. Shekriladze, I. G. and Gomelauri, V. I., "Theoretical Study of Laminar Film Condensation of Flowing Vapor," Int. J. of Heat Mass Transfer, V. 9, pp 581 - 591, 1966.

9. Denny, V. E. and Mills, A. F., "Non-Similar Solutions for Laminar Film Condensation on a Vertical Surface," Int. J. of Heat Mass Transfer, V. 12, pp 965 - 979, 1969.

10. Mayhew, Y. R., Griffiths, D. J., and Phillips, J. W., "Effect of Vapor Drag on Laminar Film Condensation on a Vertical Surface," Proc. Instn. of Mech. Engrs., V. 180 (3J), pp 280 - 289, 1965 - 66.

11. Mayhew, Y. R. and Aggarwal, J. K., "Laminar Film Condensation with Vapor Drag on a Flat Surface," Int. J. of Heat Mass Transfer, V. 16, 1944 - 49, 1973.

12. Denny, V. E. and South III, V., "Effects of Forced Flow, Noncondensables, and Variable Properties on Film Condensation of Pure and Binary Vapors at the Forward Stagnation Point of a Horizontal Cylinder," Int. J. of Heat Mass Transfer, V. 15, pp 2133 - 2142, 1972.

13. Nicol, A. A. and Wallace, D. J., "Condensation With Appreciable Vapor Velocity and Variable Wall Temperature," Steam Turbine Condensers, NEL Report No. 619, pp 27 - 38, 1976.

14. Silver, R. S., "An Approach to a General Theory of Surface Condensers," Proc. Instn. Mech. Engrs., V. 178, pp 339 - 376, 1963 - 64.

15. Wallis, G. B., "Use of the Reynolds Flux Concept for Analyzing One-Dimensional Two Phase Flow, Int. J. of Heat Mass Transfer, V. 11, pp 445 - 458 and 459 - 472, 1968.

16. Fujii, T., Vehara, H. and Kurata, C., "Laminar Filmwise Condensation of Flowing Vapor on a Horizontal Cylinder," Int. J. Heat Mass Transfer, V. 15, 235 - 246, 1972.

17. Nobbs, D. W. and Mayhew, Y. R., "Effect of Downward Vapor Velocity and Inundation on Condensation Rates on Horizontal Tube Banks," Steam Turbine Condensers, NEL Report No. 619, pp 39 - 52, 1976.

18. Nichol, A. A., Bryce, A., and Ahmed, A. S. A., Condensation of a Horizontally Flowing Vapor on a Horizontal Cylinder Normal to the Vapor Stream, paper presented at Sixth International Heat Transfer Conference, Toronto, Canada, August 7 - 11, 1978.

19. Fujii, T., Honda, H. and Oda, K., "Condensation of Steam on a Horizontal Tube - The Influence of Oncoming Velocity and Thermal Conduction at the Tube Wall,".

20. Fujii, T., Uehara, H., and Oda, K., "Filmwise Condensation on a Surface with Uniform Heat Flux and Body Force Convection," Heat Transfer - Japanese Research, V. 1, no. 4, pp 76 - 83, 1972.

21. Holman, J. P., Heat Transfer, p 204, McGraw - Hill, 1976.

22. Schlichting, H., Boundary Layer Theory, p 160, McGraw - Hill, 1968.

23. Özisik, M. N., Boundary Value Problems of Heat Conduction, pp 338 - 345, International Textbook Co., 1968.

24. Fairweather, G., Finite Element Galerkin Methods for Differential Equations, pp 21 - 66, Marcel Dekker, Inc, 1978.

25. Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, pp 166 - 168, Oxford: Clarendon Press, 1959.

26. Mills, A. F., Tan, C., and Chung, D. K., "Experimental Study of Condensation from Steam-Air Mixtures Flowing Over a Horizontal Tube: Overall Condensation Rates," Proc. Fifth Intl. Heat Transfer Conf., pp 20 - 23, 1974.

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